Energy Research and Development Division
FINAL PROJECT REPORT

GHG EMISSION BENEFITS AND AIR QUALITY IMPACTS OF CALIFORNIA RENEWABLE INTEGRATION AND ELECTRIFICATION

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PREPARED BY:

Primary Author(s):
Siavash Ebrahimi
Michael Mac Kinnon
Katie Leong
Jack Brouwer, Ph.D.

Advanced Power and Energy Program
University of California, Irvine
221 Engineering Laboratory Facility
Irvine, California 92697-3550
Phone: 949-824-7302| Fax: 949-824-7423
http://www.apep.uci.edu

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Prepared for:

California Energy Commission

Yu Hou
Contract Manager

Aleecia Gutierrez
Office Manager
Energy Generation Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

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PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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- Renewable Energy Technologies
- Transportation

GHG Emission Benefits and Air Quality Impacts of California Renewable Integration and Electrification is the final report for the Air Quality Implications of Electrification and Renewable Energy Options project (contract number 500-09-040) conducted by Advanced Power and Energy Program. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

Assembly Bill 32 requires the State of California to reduce greenhouse gas emissions to 80 percent below 1990 levels by 2050 to prevent further climate change. While decarbonizing the power supply sector is an important emissions mitigation strategy, it cannot lead to aggressive reductions alone since only 21 percent of total statewide greenhouse gas emissions originate from power generation. Widespread electrification—the process of replacing direct fossil fuel use with electricity—in combination with other energy efficiency measures is essential for meeting deep emission reduction targets. However, there has previously been little understanding of possible requirements for implementing these strategies.

In this study, the research team investigated the infrastructure transformation and technology development paths necessary for widespread electrification and decarbonization of the power sector. Using detailed modeling of infrastructure stocks and economic dispatch of the electric grid, they analyzed the grid and the emission impacts of electrifying end-use sectors while decarbonizing power generation. The researchers then developed spatially and temporally resolved emissions fields and created a detailed simulation of atmospheric chemistry and transport to determine air quality impacts throughout the state. The research team simulations included several scenarios for high renewable use and end-use electrification for the years 2020, 2030, and 2050.

Results showed that decarbonizing the power sector without electrifying end-use sectors would reduce greenhouse gas emissions by a maximum of only 6 percent, while implementing both strategies will yield up to 33 percent reductions compared to 1990 levels. Predictions of air quality impacts were mixed. In some scenarios, when both the electric power generation and electrified end-uses are both implemented, the criteria pollutant emissions dynamics lead to worse air quality, while in other cases (for instance, when smart grid and smart electric vehicle charging are widely used) air quality improvements were concomitant with greenhouse gas emissions reductions.

Keywords: electricity, renewable energy, electrification, fuel switching, buildings, residential, commercial, industrial, transportation, environmental, climate change, greenhouse gas, criteria pollutant, air quality

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EXECUTIVE SUMMARY

Introduction

Climate change, air pollution, and energy security are global challenges that jeopardize public and ecosystem health, as well as economic and political stability. Without long-term planning and immediate action, continued release of greenhouse gases—primarily from combustion of fossil fuels and industrial processes—will result in further climate change, increasing the risk of severe and irreversible impacts for humans and ecosystems. An integrated mitigation approach combining deployment of energy efficiency measures, decarbonization of the electricity generation sector, and transformation of end-use fuels can be a feasible and cost-effective solution.

Assembly Bill 32 (AB 32) mandates that the State of California reduce greenhouse gas emissions to 1990 levels by 2020, which is equivalent to 30 percent drop compared to business-as-usual projections. In addition, AB 32 has regulated an aggressive greenhouse gas emissions reduction target of 80 percent below the 1990 level by 2050. Meeting these greenhouse gas emission reduction targets requires detailed analysis and long-term planning due to complexity and dependency on energy systems.

There are several pathways for addressing energy and environmental issues, each capable of reducing emissions while enhancing energy security. Many of these solutions are feasible and cost-effective today, while others are likely to be viable in the future. As technologies advance, costs shrink and energy competitiveness evolves. An integrated mitigation approach must consider both greenhouse gas and air quality impacts of policies. In addition, such an integrated approach must combine deployment of energy efficiency measures, decarbonizing power generation and transformation of end-uses to produce a feasible and cost-effective solution that can both reduce greenhouse gas emissions and improve air quality.

Project Purpose and Process

The goal of this study is to incorporate detailed understanding of infrastructure transformation and the technology development and implementation scenarios required for achieving ambitious emissions reduction goals. The research team used detailed computer modeling of energy infrastructure, economic dispatch of the electric grid, spatial and temporal resolution of emissions, and atmospheric chemistry and transport to explore and analyze the impacts of electrifying end-use sectors while decarbonizing power generation on electric utility grid dynamics, emissions dynamics, and air quality.

Project Results

The results of the study showed that replacing gas-fired end-uses with highly efficient electric technologies while simultaneously decarbonizing the power generation sector by installing higher and higher capacities of renewable resources would reduce greenhouse gas emissions. Reducing emissions from combustion technologies in various sectors typically translates to air quality improvements in levels of both ozone and particulate matter up to 2.5 micrometers in size, where impacts vary markedly by pollutant, sector, horizon year, season, and location.

Implementing these strategies poses some challenges, however. Decarbonizing the electricity generation sector involves a strong shift towards renewable power generation. Greater levels of renewable energy use pose new challenges to the electric grid due to geographical dependency, transmission constraints and, most of all, due to the intermittency and uncontrollability of renewable power. The intermittent and uncontrollable nature of renewable power requires higher flexibility in the electric grid through a portfolio of supply- and demand-side technologies such as highly dispatchable power plants, energy storage, distributed generation, and demand response.

Furthermore, the increased electricity demand that will result from electrification, combined with the altered grid dynamics from intermittent renewable penetration, can result in localized worsening of air quality at sites of emitting power generators. In all of the scenarios the researchers investigated, they observed two general trends: (1) emissions increases and dynamic changes were typically point source emissions (fueled power plants), while (2) emissions decrease due to electrification were both point sources and area sources (residential water heaters and gas stoves).

Thus, increasing penetrations of renewable power must be accompanied by higher flexibility in the electricity grid. Implementing energy efficiency measures and decarbonizing the power supply sector as much as possible are important emissions mitigation strategies; however, applying these strategies alone will not be sufficient to meet deep emission reduction targets. Achieving such goals requires not only transforming the way energy is produced and delivered, but also evolving the way energy is consumed. Therefore, extensive electrification—switching from using direct fuel to electricity—is an essential step toward meeting deep emission reduction targets.

Benefits to California

The total annual greenhouse gas emissions of end-use sectors are reduced by at least 1 percent compared to the base case, while the power sector exhibited greenhouse gas emission increases by as much as 47 percent due to dispatch of fossil fuel power plants to meet the additional demand of electrification. Based on the explored scenarios, the research team predicts that total greenhouse gas emissions, from end-use sectors and power sector, can be reduced by electrification and reliance on renewable power. Scenarios that electrified the combined residential, commercial, transportation and industrial sectors showed the greatest impact with net greenhouse gas reductions as high as 111 $MMTCO_2e$ (27.4 percent) in 2050. In addition, scenarios in which electrification of the transportation sector with smart charging strategy led to greater greenhouse gas emission savings; this is due to higher flexibility of demand and enhanced load balancing of smart charging strategy, which results in lower renewable curtailment, smaller grid dynamics, and consequently lower emissions.

CHAPTER 1: Introduction

The State of California is mandated by Assembly Bill 32 (AB 32) to reduce GHG emissions to 1990 levels by 2020, which is equivalent to a 30% drop compared to business-as-usual projections. In addition, AB 32 has regulated an aggressive GHG emissions reduction target of 80% below the 1990 level by 2050. Meeting these greenhouse gas (GHG) emission reduction targets requires detailed analysis and long-term planning due to complexity and dependency on energy systems. There are multiple paths to achieve GHG emission reduction goals, all comprising efficiency improvements, electrification, and higher levels of renewable resources. Therefore, a detailed study of supply and demand alternatives must be conducted to evaluate the requirements of future energy grid that can achieve GHG reduction goals (Wei, et al., 2013). It was found that after employing the maximum feasible amount of emission reduction measures, there is no alternative to extensive deployment of electrification in order to achieve the GHG reduction targets (Williams, et al., 2012)..

The goal of this study is to incorporate detailed understanding and physical representation of future grid infrastructure and required complementary technologies that will address the deployment of electrification to not only meet the AB 32 GHG emission reduction targets, but to also reduce the criteria pollutant emissions to meet the National Ambient Air Quality Standards.

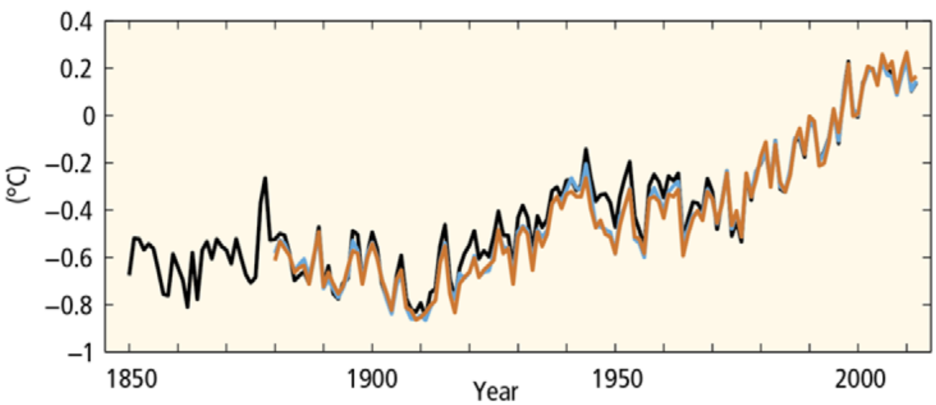
CHAPTER 2: Background

Global warming, air pollution and energy security are three of the greatest challenges our world encounters, threatening public and ecosystem health as well as economic and political stability. They will evolve the way energy is supplied and converted in end-uses over the next century with huge increase in levels of clean and secure energy while reducing energy demand in all economic sectors. In this section, energy issues and potential solutions are introduced through a review of current literature. In addition, energy and emission statistics of California are presented and the feasibility of proposed solutions is discussed.

2.1 Global Warming

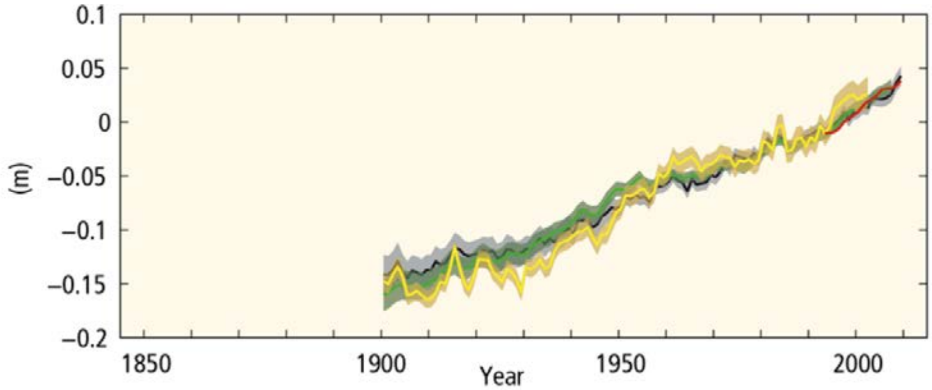
Human activities have greatly influenced the climate system over the last two decades causing global warming and sea level rise. The global mean surface temperature increased by 0.85 Celsius degrees from 1880 to 2012 (Figure 1), and the average sea level rose by 0.19 meter (Figure 2) over the period 1901 to 2010. The rate of global sea level rise over the last decade has been greater than the rate during the previous two millennia (Intergovernmental Panel on Climate Change, 2014).

Figure 1: Global Mean Surface Temperature Change



Source: (Intergovernmental Panel on Climate Change, 2014)

Figure 2: Globally Averaged Sea Level Change

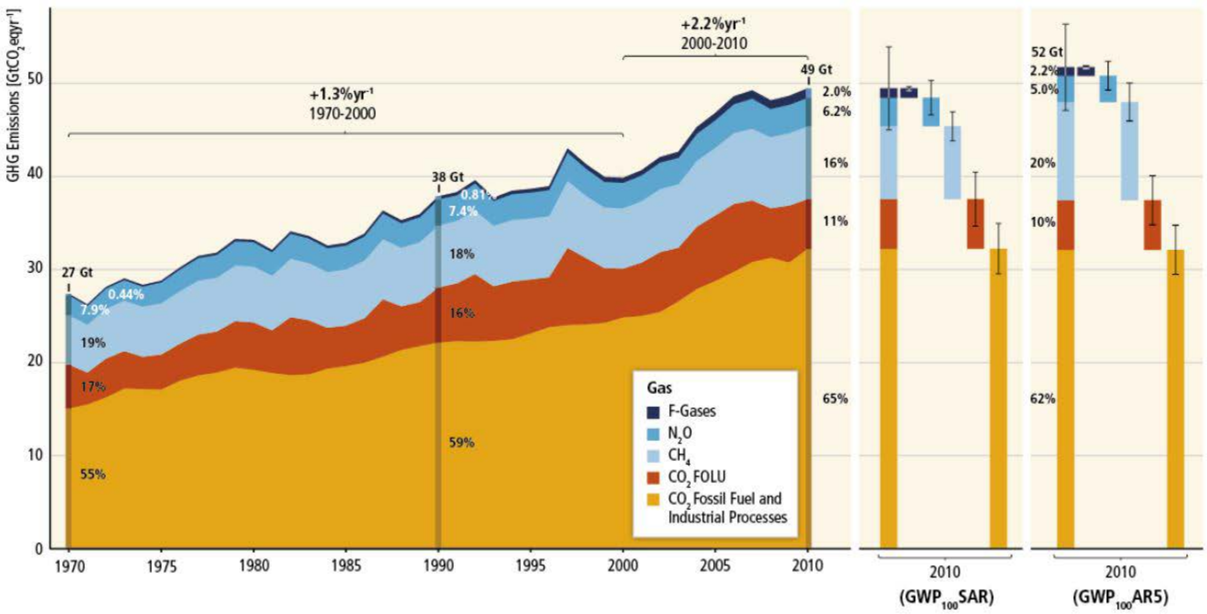


Source: (Intergovernmental Panel on Climate Change, 2014)

Climate change has caused significant impacts on natural systems across the world, ranging from ecosystems to hydrological systems. Recent climatic extremes, such as heat waves, wildfires, floods, and droughts have revealed extensive vulnerability of global natural systems (Intergovernmental Panel on Climate Change, 2014). In addition, global warming can be harmful to human health by increasing the incidence of infectious illnesses such as tuberculosis and waterborne diseases such as cholera (Epstein, 2000).

The main reason of climate change is the augmented concentrations of anthropogenic greenhouse gas emissions, mainly driven by economic and population growth since the industrial revolution. Total anthropogenic emissions of greenhouse gases have continued to elevate over 1970 to 2000, followed by a larger absolute growth between 2000 and 2010, in spite of increasing number of mitigation policies. The primary GHG emission is CO_2, which is emitted from combustion of fossil fuels and industrial processes, contributing to 78 percent of the overall GHG emission increase from 1970 to 2010 (Figure 3).

Figure 3: Total Annual GHG Emissions by Gases

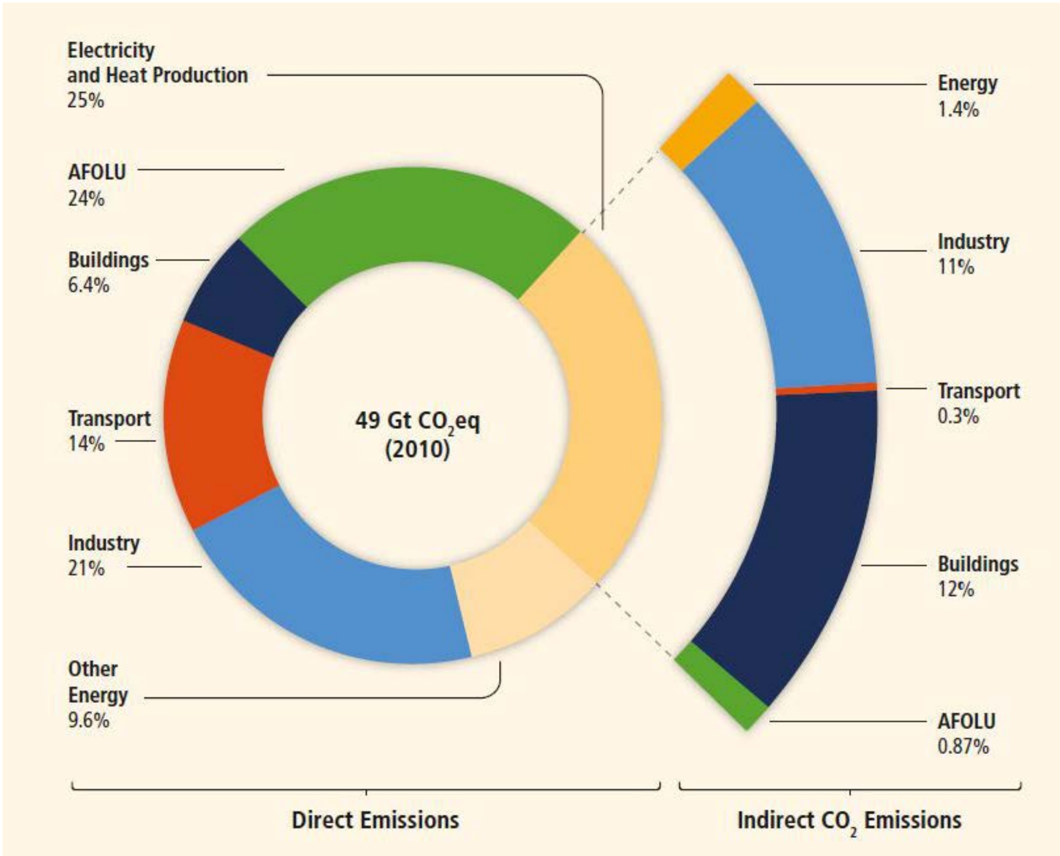


Source: (Intergovernmental Panel on Climate Change, 2014)

Annual anthropogenic GHG emissions have risen from 39 GtCO2eq in 2000 to 49 GtCO2eq in 2010, where this growth was primarily attributed to emissions from energy supply (47 %), industry (30 %), transportation (11 %) and buildings (3 %) sectors. GHG emissions have increased in all sectors since 2000, except in agriculture, forestry and other land use (AFOLU) sector. Figure 4 shows the breakdown of total annual GHG emissions by economic sector in 2010 (Intergovernmental Panel on Climate Change, 2014).

Even if the atmospheric concentrations of GHG emissions had been stabilized in the year 2000, there was already a commitment to further global warming of over half degree and additional sea level rise by the end of the century primarily due to thermal expansion of seawater (Meehl, et al., 2005). Hence restraining global warming would require rapid action on significant reduction of GHG emissions; however, substantial long-term commitment to sea level rise caused by thermal expansion may be unavoidable (Wigley, 2005).

Figure 4: Total Annual GHG Emissions by Economic Sector in 2010



Source: (Intergovernmental Panel on Climate Change, 2014)

Continued release of greenhouse gas emissions will result in further global warming, increasing the possibility of severe and irreversible impacts for humans and ecosystems. Without further mitigation policies beyond those in position today, global warming will lead to very high risk of extensive global dis-benefits by the end of the century.

There are several mitigation pathways for controlling global warming, each involving significant emissions reductions of greenhouse gases, while requiring substantial technological, economic, and social adaptations. An integrated mitigation approach combining reduction measures for energy consumption and GHG emissions of end-use sectors, decarbonizing energy supply, and enhancing carbon sinks in land-based sectors can be a feasible and cost-effective solution. However, any mitigation approach would suffer from delayed responses in both GHG emissions due to inertia in technological, social and political systems as well as in global temperature because of inertia in the climate system. Therefore, achieving global warming objectives would require early initiation of widespread and concerted global mitigation efforts (Peters, et al., 2013).

Anthropogenic GHG emissions from end-use energy sectors can be effectively reduced through systemic technical and behavioral mitigation measures such as transformation of transportation fuel and infrastructure, implementation of energy efficiency policies, and widespread upgrading of industrial facilities. In addition, decarbonizing electricity generation sector, through deployment of renewable energies and CO_2 capture and storage (CCS) technologies, is a strategic component of effective mitigation approaches in achieving GHG reduction targets (Intergovernmental Panel on Climate Change, 2014).

Global warming mitigation pathways are likely to reduce costs for achieving air quality and energy security objectives, with substantial co-benefits for human health, ecosystem impacts and sufficiency of energy resources.

2.2 Air Pollution

Clean air is one of the essential needs for human health. Since the drastic growth of global economy and population, air pollution has been a significant threat to human health worldwide and it continues to be one of the primary concerns to environmental and public health. Urbanization and rapid growth of population alongside gigantic development of transportation and industry sectors are the main causes of air pollution in urban areas.

There are several adverse health impacts associated with short-term and long-term exposure to air pollution ranging from subclinical effects, such as physiological changes in respiratory and cardiovascular systems, to clinical symptoms, hospital admissions, and finally to death (Seaton, et al., 1995) (Brunekreef & Holgate, 2002) (Chen & Kan, 2008).

Over the past decades, ambient air pollution in developed countries has improved dramatically thanks to technological advances and stringent air quality regulations. However, developing countries are still suffering from relatively high levels of air pollution. Although concentrations of air pollutants from fossil fuel combustion is much lower compared to 50 years ago, other components such as photochemical air pollution, characterized by high levels of ozone in warm climates, have obtained paramount importance. In addition, increasing concentrations of nitrogen oxides emitted from growing number of motor vehicles is of great concern to air quality in urban areas (Fenger, 2008) (McDonald, et al., 2012)..

Besides regional consequences of air pollution that are of great concern to public health, universal transport of air pollutants, including ozone, aerosols and nitrogen oxides, are serious threats to natural ecosystems and global climate system. Therefore, air pollution has to be considered as a global issue and efforts should be made in order to improve air quality in every country (Akimoto, 2003).

2.3 Energy Security

Energy security can be defined as the availability of sufficient and reliable energy supplies at affordable prices. It is one of the primary objectives of public policy, coexisting with other major goals such as economic growth and environmental protection. The issue is critical to the global economy since energy is the driving force for all economic sectors.

Over the past decades, the issue of energy security has gained substantial attention due to dramatic elevation of energy prices, shortcoming of regional energy supply and impending depletion of oil reserves. Oil supply has been the primary concern of public security for a few decades; however, the concept of energy security is being extended to include other forms of energy such as electricity because of extensive deployment of fuel switching (Bielecki, 2002).

The growing reliance of energy consuming countries on oil and gas imports from limited number of producing countries, often with low political stability, has deteriorated the global interim energy-security. Rising energy insecurity due to increasing global energy demand, insufficiency of energy policies, and political instability of energy producing countries will cause adverse impacts on future global economic stability (Umbach, 2010).

The United States has performed poorly in achieving energy security goals compared to many other countries, with only improving energy intensity and fuel economy from 1970 to 2007. Over this period, economic and population growth has caused 23% elevation in total energy demand, leading to increased dependency on energy supplies from insecure and politically unstable countries (Sovacool & Brown, 2010).

There are several approaches for achieving energy security objectives, each encompassing 1) energy consumption reduction through conservation or energy efficiency improvement, 2) replacement of insecure energy supplies with secure ones through diversification or deployment of alternative energy resources, and 3) restricting new demands to secure domestic energy sources such as renewable power (Hughes, 2009).

Growth of energy demand is a critical factor in determining the pathway for achieving energy security goals; however, conservation and energy efficiency by their own cannot provide the adequate energy consumption reductions required to reach energy independency. Therefore, any mitigation approach must compromise significant reductions in oil imports and increased resilience of energy resources (McCollum, et al., 2014).

2.4 Potential Solutions to Energy Challenges

There are several pathways for addressing energy issues each capable of reducing emissions while enhancing energy security. Many of these solutions are feasible and cost-effective today while others are likely to be viable in the future, as technologies advance, costs shrink, and energy competitiveness evolve. There is no unique solution for tackling all global energy challenges, but potential solutions will compromise a range of options that will vary geographically and with time (Bauen, 2006). Moreover, the energy roadmap must be established in such a way that connect the gap between planning for shallower, near-term solution depending entirely on commercially available technologies and deeper, long-term solution that will be based on technologies that are not yet commercialized. There is a global consensus that any proposed solution to the energy challenges must consist of three essential components: energy efficiency improvement, transforming electricity supply sector and fuel switching (Williams, et al., 2012).

2.4.1 Energy Efficiency

Over the past three decades, U.S. economy doubled and the population grew by 35 percent; however, energy intensity plunged by half owing to tremendous energy efficiency improvements (US Census Bureau, 2014) (U.S. EIA, 2014). The U.S. economy is expected to continue to grow 2.2 percent per year through 2030 (Bureau of Economic Analysis, 2014); unless considerable energy efficiency measures are deployed, U.S. energy intensity would increase by 39 percent in 15 years that could result in huge elevation in oil and gas imports. Therefore, energy efficiency improvement is essential for enhancing energy security, developing the economy, and improving public health.

Building sector offers the greatest potential for implementing cost-effective energy efficiency measures. Widespread deployment of energy-efficient technologies in buildings by itself could eliminate the necessity of expanding U.S. electricity supply sector. Energy efficiency measures can be implemented in buildings through improvements in the building envelope, HVAC systems, lighting, and electronic appliances. In addition, on-site energy resources such as rooftop PV or solar hot water can dramatically reduce the reliance of energy consumers on electric grid and fossil fuels (National Academy of Engineering, 2010).

In the industrial sector, energy savings can be achieved by employing cutting-edge technologies, such as combined heat and power, new manufacturing techniques, enhanced chemical processes, advanced materials, and optimized process heating technologies. However, integration of new technologies poses technical risks and uncertainties that may interrupt the plant operation or worsen the product quality due to uniqueness of each industrial plant.

Moderate efficiency improvements can be made in some modes of transportation including air and rail transportation, heavy-duty trucks, and freight transport. Energy savings can be primarily achieved through implementing modern gasoline and diesel engines, enhanced transmission systems, advanced lightweight material, and improved aerodynamics. However, substantial increase in traffic is projected to prevail over efficiency improvements, yielding greater overall energy consumption (Lave, 2009).

Finally it must be noted that energy efficiency improvement is not possible without government support, including regulations and tax policies, and public awareness.

2.4.2 Decarbonizing Power Supply Sector

There are three alternative technologies commercially available for decarbonizing electricity supply sector: renewable energy resources, nuclear power, and fossil fuels with carbon capture and storage. Renewable power is the first and foremost option for decarbonizing electricity generation since it is abundant, sustainable, and green. Previous studies have shown that multiple combinations of renewable resources including solar, wind, geothermal, hydropower, and biopower are capable of meeting 80% of total U.S. electricity demand in 2050 while achieving deep reductions in electric sector emissions. However, greater levels of renewable power pose new challenges to electric grid due to geographical dependency, transmission constraints and most importantly power output variability. Therefore, increasing penetrations of renewable power must be accompanied by higher flexibility in the electricity grid through a portfolio of supply- and demand- side technologies, including energy storage, transmission and distribution expansion, higher responsive loads, and enhanced power system operation (Mai, et al., 2014).

Nuclear power can also play a key role in decarbonizing the power supply sector owing to its zero emissions, high reliability, and low operation costs. However, nuclear power has its own challenges including base load power generation, safety issues, waste management, and high investment costs. Over the past few years, share of nuclear energy to the global electricity demand has dropped dramatically in reaction to the 2011 Fukushima nuclear disaster (Chu & Majumda, 2012), placing the global energy policy and future of nuclear power at juncture (Mez, 2012). Nevertheless, the safety issues has been substantially improved in new generations of nuclear power plants, and global efforts for addressing other concerns are increasing, but minimal progress has been made in solving waste management issues. Therefore, addressing the existing challenges and safe operation of plants are essential for raising the share of nuclear power in global power supply (Ahearne, 2011).

Fossil fuels continue to be the primary source of power supply over the next decade due to increasing electricity demand, inertia in extensive deployment of renewable resources, and safety concerns regarding nuclear power. Although improvements in thermodynamic efficiency of power plants, cogeneration of heat and power (CHP), and heat recovery contribute to mitigation of power sector emissions, these technologies are not sufficient for achieving emission reduction goals. Hence, implementing carbon capture and storage (CCS) from coal and natural gas power plants is pivotal (Chu & Majumda, 2012).

Furthermore, a medium-term approach is likely to include replacement of coal power plants by state-of-the-art combined natural gas plants that offer lower emissions and higher flexibility for balancing the grid (Renssen, 2012). Within the western grid of United States, all existing coal power plants are planned to retire by the end of their lifetime of 30 years (Williams, et al., 2012).

2.4.3 End-Use Fuel Switching

Implementing energy efficiency measures and greening power supply sector to the maximum feasible extent are not sufficient by their own to meet deep emission reduction targets. Achieving such goals requires not only transforming the way energy is produced and delivered but also evolving how energy is consumed. Apparently, unless extensive energy efficiency measures are employed, end-use energy consumption and corresponding GHG emissions continue to increase due to growing trends of population and economy. Improving end-use energy efficiency without transitioning away from fossil fuels might be a proper short-term strategy, but is not certainly adequate for achieving long-term goals.

Current energy policies are primarily focused on decarbonizing electricity generation, while overlooking end-use energy sectors, which contribute to more than 50 percent of the gross annual GHG emissions worldwide (Figure 2-4). Even complete decarbonization of power supply sector cannot lead to aggressive GHG emission reductions since only 25 percent of total global GHG emissions are attributed to electricity generation. Therefore, extensive electrification—that is to say, switching direct fuel use to electricity—is essential for meeting deep emission reduction targets (Williams, et al., 2012).

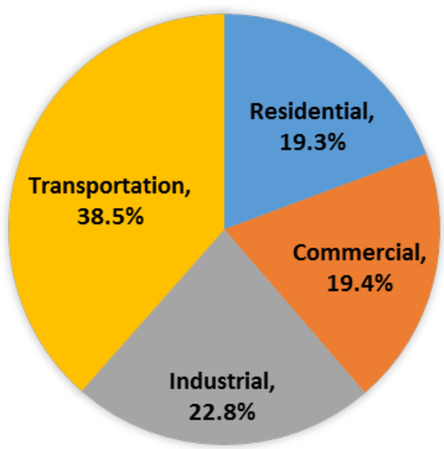
In the future, electricity should be used to provide most of the energy consumed in our cars, building, and industry. However, electrifying end-use sectors is meaningless if the electricity is supplied mainly from fossil fuel power plants. In other words, electrification only makes sense if the power sector is fully decarbonized (Renssen, 2012).

2.5 California Energy Demand

California heavily relies on energy, having the second greatest energy demand (U.S. Energy Information Administration, 2012) while encompassing the largest population and economy in the nation. Due to extensive enforcement of energy efficiency policies as well as deployment of alternative technologies, California is recognized as the leader of energy use in the nation. In 2012, California's per capita energy use ranked 49th in the nation, which was mainly due to the state's moderate climate as well as the energy efficiency regulations.

Transportation is the dominant end-use energy sector, comsuming about 39 percent of total statewide energy use in 2012 (Figure 5), primarily due to the presence of airports, military bases, and extensive numbers of motor vehicles. Industrial sector, the second largest energy-intensive sector, accounted for 23 percent of the overall statewide energy use, mainly consumed for industrial activities such as oil/gas extraction and manufacturing. Residential and commercial sectors had about the same contribution (19%) to overall statewide energy consumption in 2012, where the majority of their energy use was associated with activities including heating, lighting and cooking.

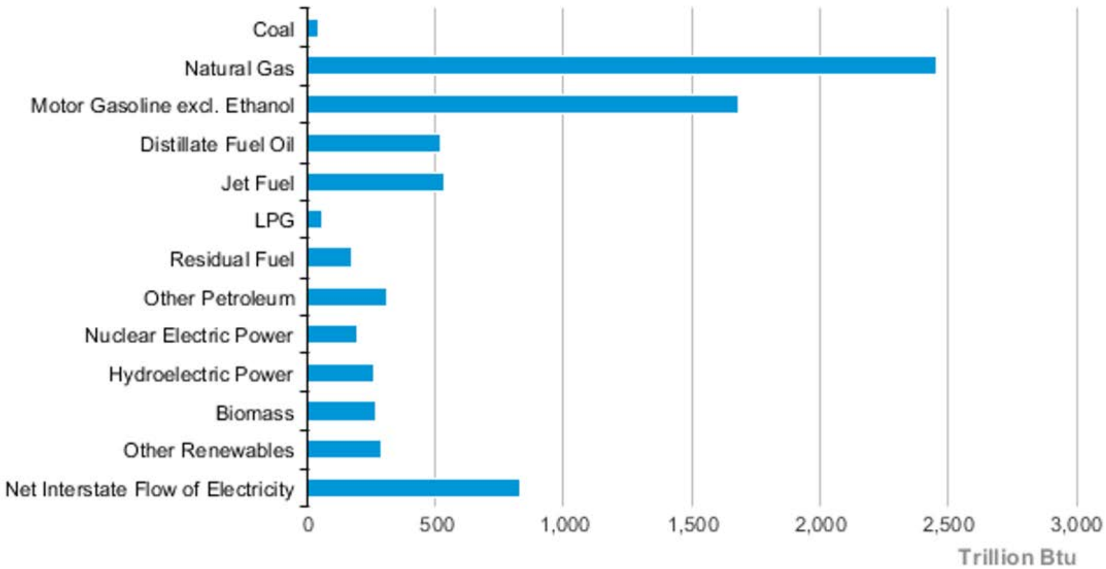
Figure 5: California Energy Consumption by End-Use Sector in 2012



Source: (U.S. Energy Information Administration, 2012)

Figure 6 displays the relative consumption of various fuels by end-use energy sectors of California in 2012. Natural gas was the most widely used fuel, supplying nearly 2500 trillion Btu of energy for different activities ranging from industrial steam generation to residential water heating. Motor gasoline, the second most commonly used fuel, contributed to about 1700 trillion Btu of California energy demand in 2012, which was primarily consumed for combustion in light-duty vehicles. Although California has no coal production and has been diminishing the electricity generation of coal-fired power plants, trivial amounts of coal was consumed by certain industrial facilities in 2012. Approximately 500 trillion Btu of energy originated from distillate fuel oil (diesel) which was mainly used to power heavy-duty vehicles, while similar amount of jet fuel was consumed by aviation activities in 2012. LPG, residual fuel and other petroleum had a gross consumption of over 500 trillion Btu by different end-use sectors of California in 2012.

Figure 6: California Energy Consumption by Fuel in 2012

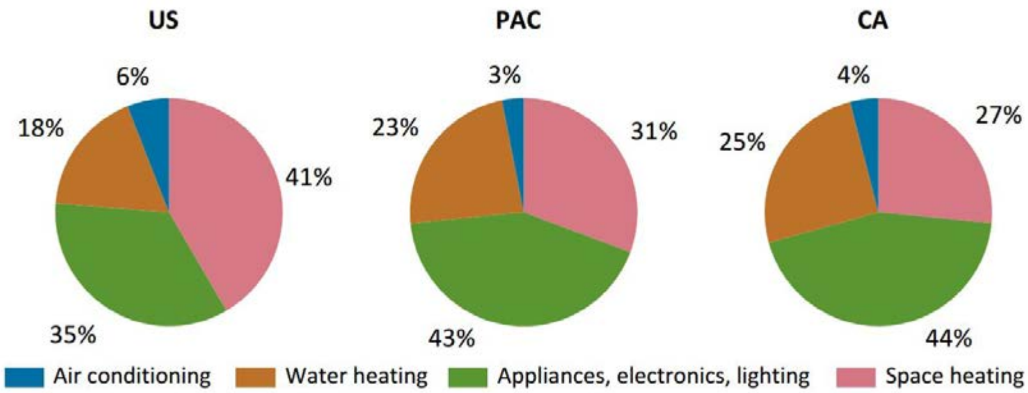


Source: (U.S. Energy Information Administration, 2012)

2.5.1 Residential

About 62 million Btu of energy is consumed annually by an average California household, which is 31 percent below the nationwide value (U.S. Department of Energy, 2009). This is mainly due to the moderate climate of California, which alleviates the reliance on energy for heating and air conditioning. An average U.S. household consumes about 47 percent of its total energy use for space heating and cooling purposes, while these two end uses combined account for only 31% of total residential energy consumption in California (Figure 7). Consequently the contribution of other residential end uses, such as water heating, to the overal residential energy use is higher in California compared to the nation.

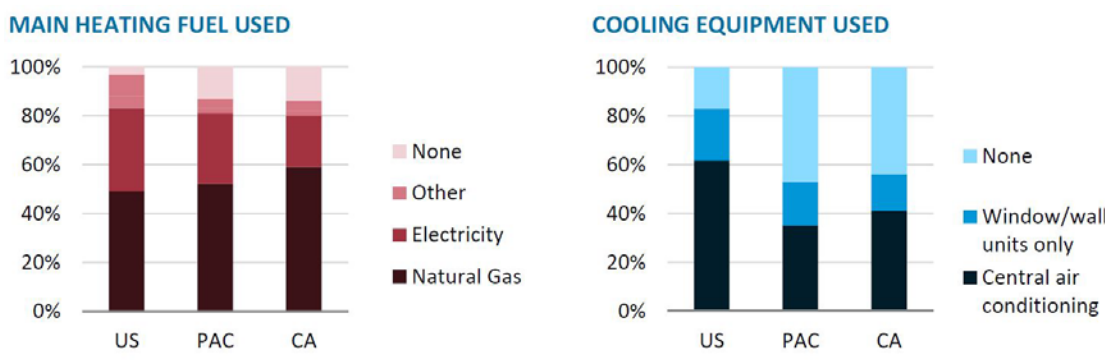
Figure 7: Residential Energy Consumption by End Use



Source: (U.S. Department of Energy, 2009)

As Figure 8 shows, natural gas was the main fuel used for heating of California homes in 2009, while electricity accounted for only 20 percent of overall heating energy use. About 10-15 percent of California homes had no heating equipment, mainly due to the mild climate of California. Other fuels such as biomass, LPG and residual fuel oil were used for heating about 5 percent of California households. Due to the moderate average temperatures (about 80°F) in summer, more than 40 percent of California homes have no cooling equipment, while more than 80 percent of nation's households use cooling equipment. The California households that use cooling equipment primarily rely on central air conditioning (U.S. Department of Energy, 2009).

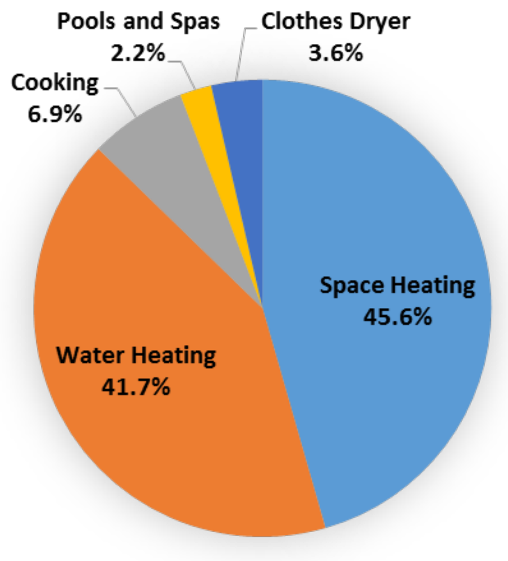
Figure 8: Heating and Cooling Equipment Used in Residential Buildings



Source: (U.S. Department of Energy, 2009)

Detailed breakdown of statewide residential natural gas consumption is plotted in Figure 9. The majority of natural gas use was attributed to space heating (45.6%) and water heating (45.6%) end uses. Cooking (6.9%), pools/spa (2.2%), and clothes dryer (3.6%) combined accounted for less than 15 percent of overall residential energy use in 2010 (CEC Demand Analysis Office, 2012).

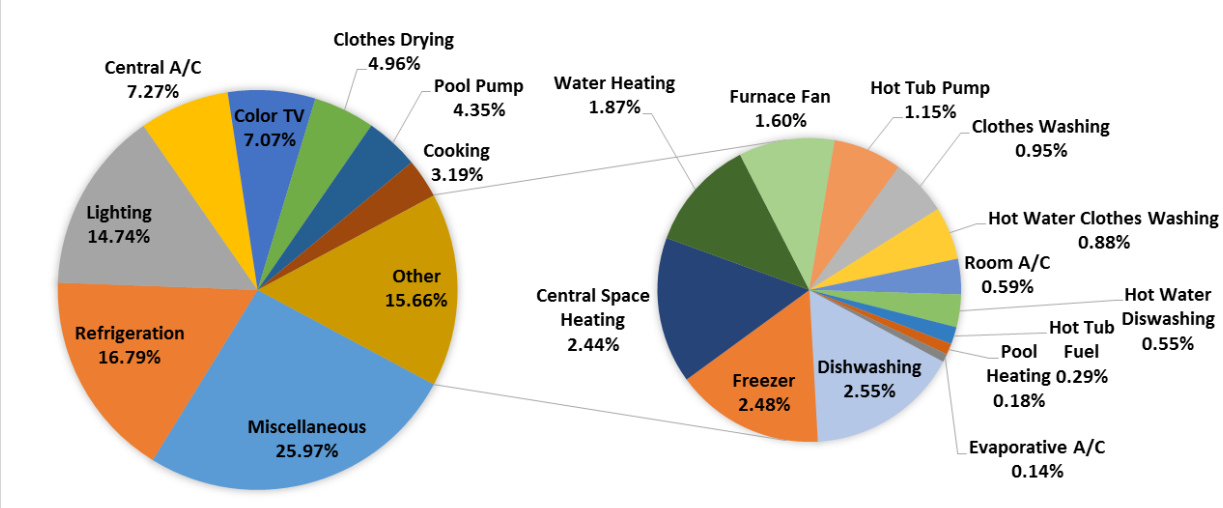
Figure 9: California Residential Natural Gas Consumption by end-use



Source: (CEC Demand Analysis Office, 2012)

Figure 10 displays the breakdown of California residential electricity consumption by end-use. More than 25 percent of total residential electricity use was attributed to miscellaneous end-uses such as computers, and electronics in 2014. Refrigeration, lighting, and central air conditioning were the next major electric power users, consuming about 16.8%, 14.7%, and 7.3% of total residential electricity consumption, respectively. Gas/electric powered end-uses including space heating (2.44%), water heating (1.87%), cooking (3.19%), clothes drying (4.96%), and pool heating (0.18%) consumed nearly 13 percent of total residential electricity use in 2014.

Figure 10: California Residential Energy Consumption by End Use

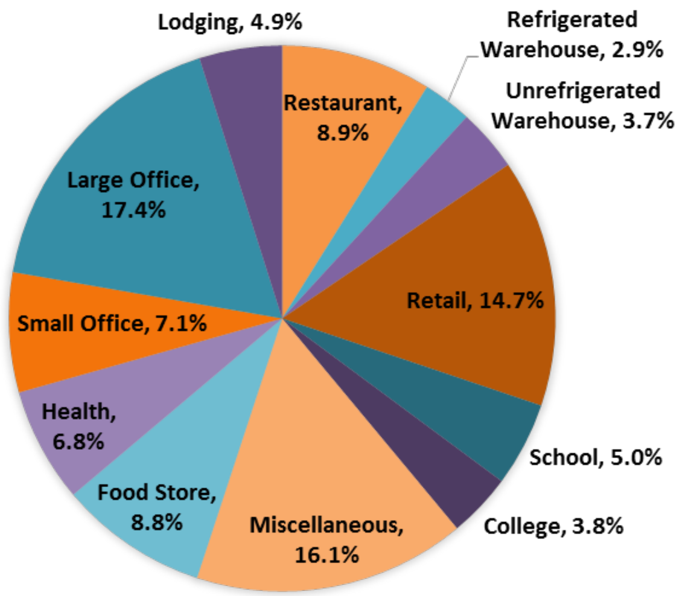


Source: (CEC Energy Assessments Division, 2014)

2.5.2 Commercial

Figure 11 and Figure 12 show the percent contribution of various commercial buildings to the total electricity and natural gas consumption. 67,707 GWh of electricity was consumed by the commercial sector of California in 2006. Approximately half of total commercial electricity use was consumed by three major buildings including large offices (17.4%) and retail (14.7%), while more than 20 percent of the total electricity consumption was associated with food-related buildings such as restaurants (8.9%), food store (8.8%), and refrigerated warehouse (2.9%).

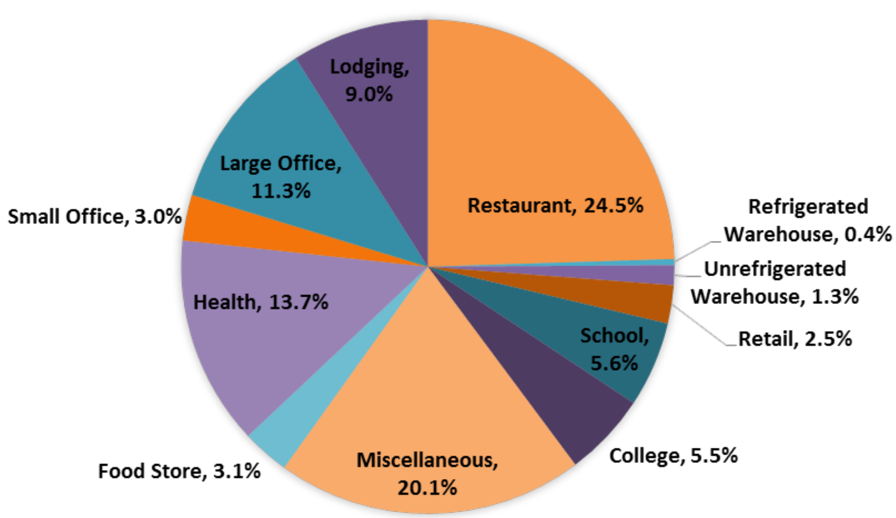
Figure 11: California Commercial Electricity Use by Building Type



Source: (Itron Inc., 2006)

In 2006, roughly 70 percent of total natural gas use was attributed to four major building types including restaurants (24.5%), health (13.7%), and large offices (11.3%). The next two major commercial consumers of natural gas were lodging and small office buildings, with constituting about 9 percent and 3 percent of overall natural gas use, respectively. Educational buildings, including college and school, combined accounted for 11.1 percent of overall natural gas use in 2006.

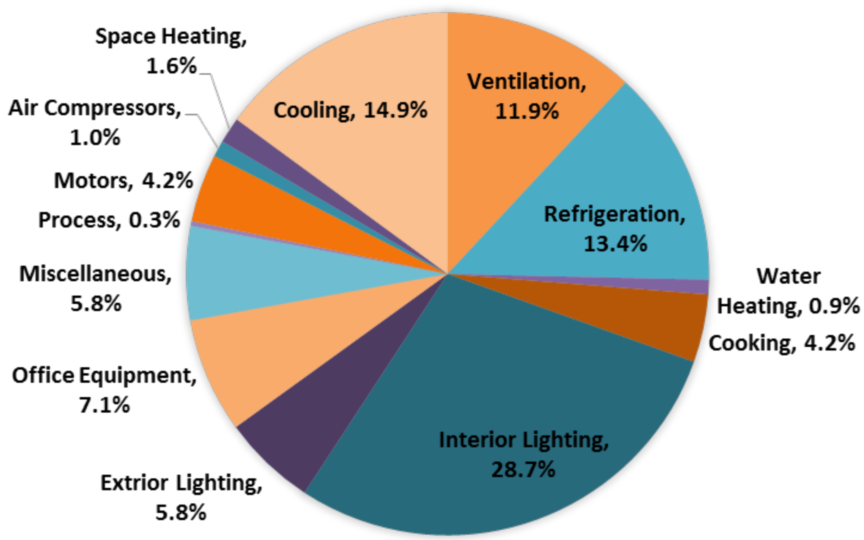
Figure 12: California Commercial Natural Gas Consumption by Building Type



Source: (Itron Inc., 2006)

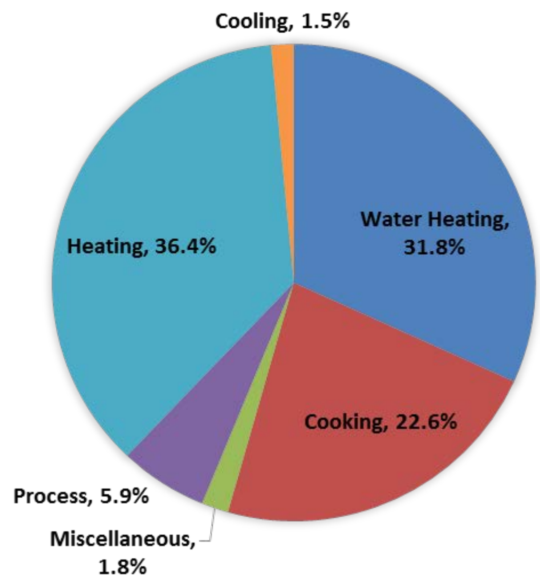
Figure 13 and Figure 14 display the percent contribution of various commercial end uses to the overall electricity and natural gas consumption. The majority of commercial electricity use is attributed to lighting (35%), air conditioning (28%), and refrigeration (13%), while heating makes up a relatively small portion (3%) of overall commercial electricity consumption. However, space heating and water heating combined accounted for over two thirds of overall commercial natural gas use in 2006. About 23 percent of the total natural gas consumption was associated with cooking and the rest 10 percent was attributed to other commercial activities, such as process heating, cooling, and miscellaneous.

Figure 13: California Commercial Electricity Consumption by End Use



Source: (Itron Inc., 2006)

Figure 14: California Commercial Natural Gas Consumption by End Use



Source: (Itron Inc., 2006)

2.5.3 Industrial

Industrial sector is the goods-producing segment of an economy, which uses facilities, processes and equipment for producing merchandise and wares. About one third of 2012 U.S. energy was consumed by industrial sector for processes including manufacturing, mining, and agriculture. Manufacturing was the most energy-intensive part of the industrial sector, consuming about 75 percent of total industrial energy use (U.S. EIA, 2014) (U.S. Department of State, 2010) . As Figure 15 illustrates, over 60 percent of total industrial energy consumption was delivered to primary manufacturing activities including petroleum refining (40.3%), bulk chemical (6.7%), nonmetallic minerals (4.6%), food processing (5.7%), pulp and paper (1.7%), and fabricated metal (1.2%) industries.

Figure 15: Total Energy Use of California Industry Subsectors by percentage, 2008

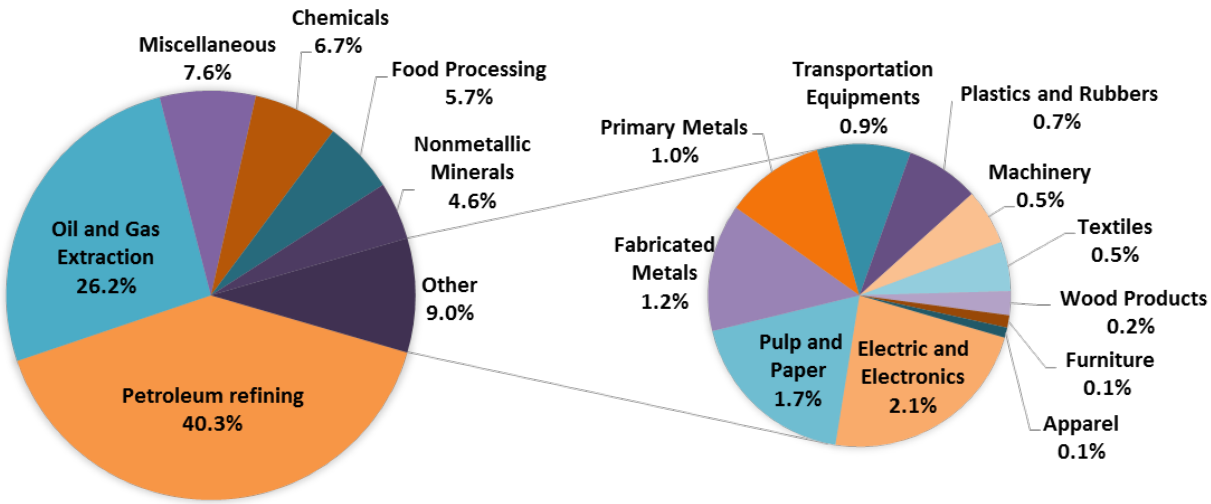
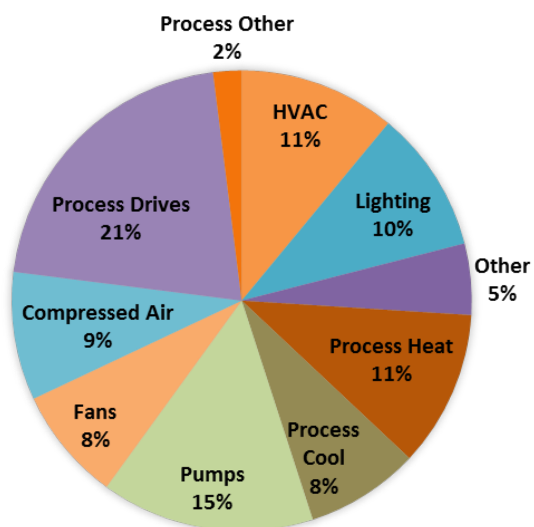


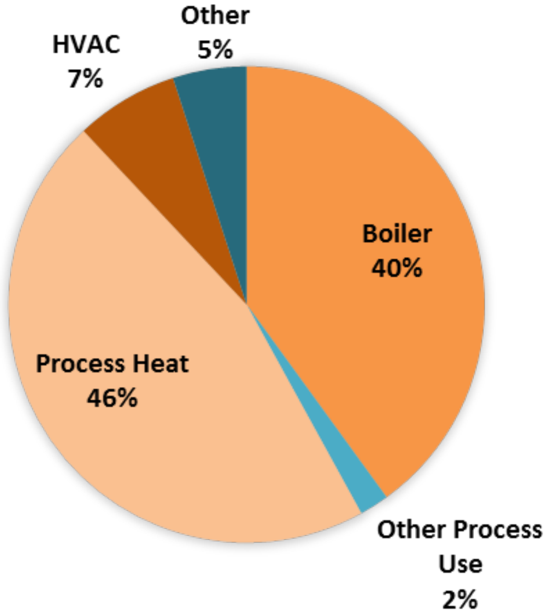
Figure 16 and Figure 17 detail the breakdown of California industrial electricity and natural gas consumption by key end uses. The process drives end use is the largest consumer, using about 21 percent of total industrial electricity consumption. Over one third of total industrial electricity use is associated with flow driving units including pumps (15%), air compressors (9%), and fans (8%). In addition, 20 percent of the total industrial electricity use is delivered to thermal processing units, while about half of the overall natural gas use is consumed by process heaters. Boilers and HVAC are the other primary natural gas users, contributing to 40 percent and 7 percent of total industrial natural gas consumption, respectively.

Figure 16: California Industrial Electricity Consumption by End Use



Source: (Friedmann, et al., 2005)

Figure 17: California Industrial Natural Gas Consumption by End Use



Source: (Friedmann, et al., 2005)

2.5.4 Transportation

There are more than 26 million passenger vehicles and 1 million trucks on California roads and highways. In 2012, California transportation consumed about three quadrillion Btu of energy, which accounted for nearly 39 percent of the total statewide energy consumption (U.S. Energy Information Administration, 2012). Figure 18 illustrates the percent contribution of various transportation modes to the overall energy consumption. Light-duty passenger vehicles dominate the transportation sector with consuming over 57 percent of total energy use. Heavy-duty trucks and aviation also make up a relatively large portion of the transportation sector with contributing to 29 percent of total energy use, combined. About 10 percent of the overall energy consumption is attributed to other modes of transportation, including light-duty trucks (2%), rail (2%), bus (1%), marine (2%) and military (3%).

Figure 18: U.S. Transportation Energy Use by Mode

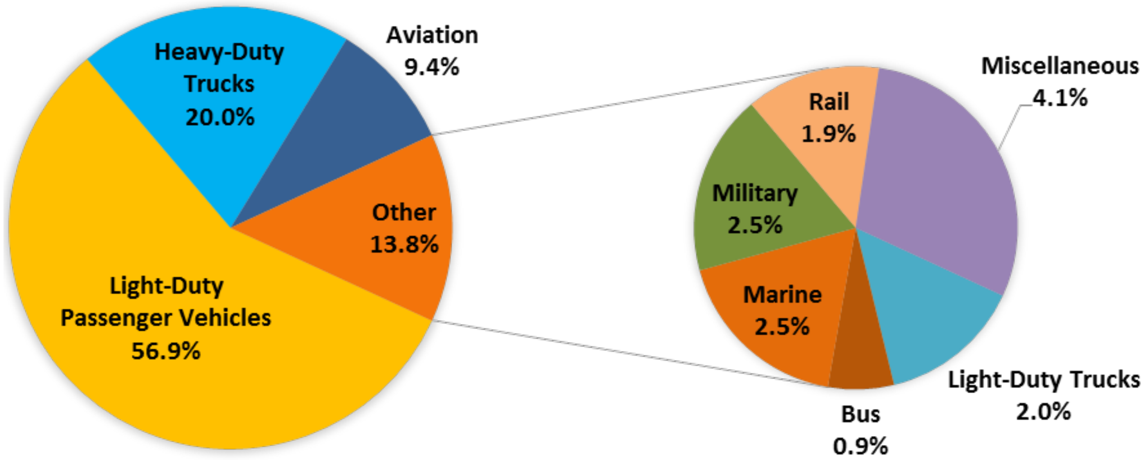
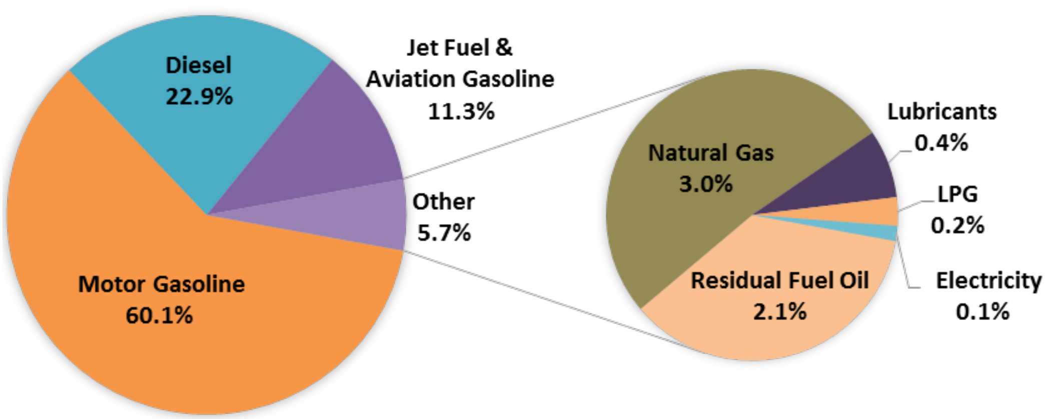


Figure 19 shows the detailed breakdown of transportation sector by fuel type. Due to the large contribution of light-duty vehicles, gasoline is the dominant transportation fuel, supplying over 60 percent of total energy demand. Diesel fuel accounts for nearly 23 percent of the overall energy use, and it is primarily consumed by heavy-duty trucks, buses and military transportation. Jet fuel and aviation gasoline combined make up 11 percent of the total transportation fuel supply, while other fuels, such as natural gas, constitute only 6 percent of the total transportation energy demand. Figure 2-18 and Figure 2-19 were plotted based on the data obtained from 2014 Annual Energy Outlook (U.S. Energy Information Administration, 2014).

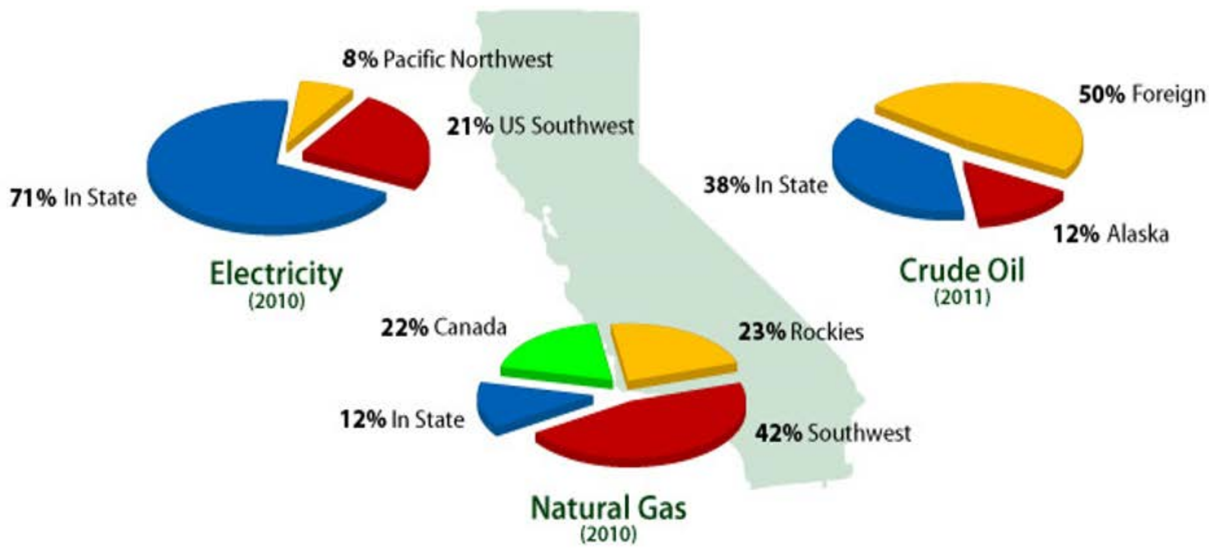
Figure 19: U.S. Transportation Energy Use by Fuel Type



2.6 California Energy Supply

California is blessed with abundant energy resources ranging from crude oil to hydroelectric power to renewable energies. However, a significant portion of its energy need is imported from out-of-state sources due to its tremendously large energy demand. Figure 20 details the breakdown of California's primary energy sources by geogrophical location. Although California has the third largest crude oil production in the nation, it still imports over 60 percent of its total oil demand from out-of-state resources. Similiarly the majority of natural gas demand is supplied by out-of-state sources, while in-state marketed natural gas, account for only 12 percent of overall demand. In 2010, over 70 percent of total electrcity demand was delivered by state-owned generators, and the rest was imported from U.S. southwest (21%) and pacific northwest (8%).

Figure 20: California's Primary Sources of Energy

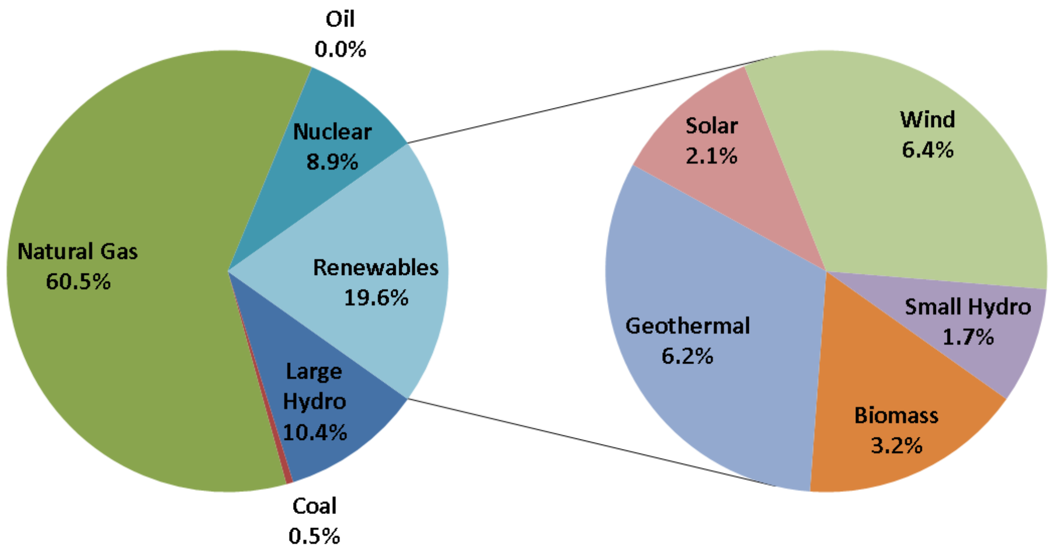


Source: (California Energy Commission, 2013)

2.6.1 California Electricity Generation

About 20,000 GWh of electricity is generated annually by massive in-state electric generators. As Figure 21 illustrates, natural gas power plants are the dominant source of electricity producing over 60 percent of total in-state generation. Large hydro and nuclear are the next major sources, constituting 10.4 percent and 8.9 percent of total in-state electricity generation in 2013. Coal and oil plants combined account for less than 1 percent of overall generation, while renewables make up a relatively large portion (20%). Wind and geothermal are the primary renewable resources with each accounting for about 6 percent of total generation. The rest of electricity demand was powered by other renewable sources including biomass (3.2%), solar (2.1%) and small hydro (1.7%).

Figure 21: California's In-State Electricity Generation Mix in 2012



Source: 2013 (California Energy Commission, 2013)

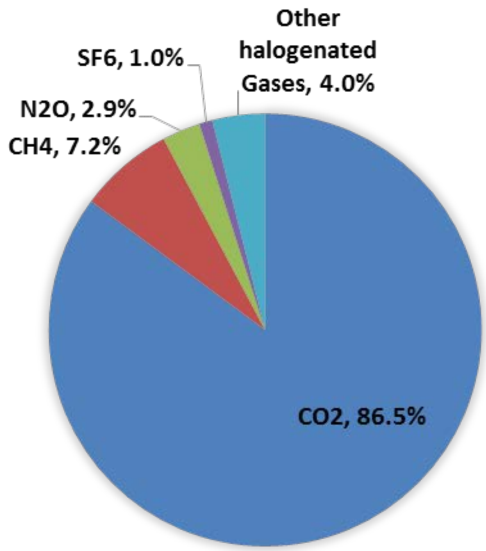
2.7 Emissions

2.7.1 Greenhouse Gases

In 1997, six gases were identified by Kyoto Protocol for emission reduction targets: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perflurocarbons (PFCs) and sulfur hexafluoride (SF6). A global warming potential (GWP) value was calculated and attributed to each gas, which represents its comparative climate impact as well as its lifetime in atmosphere. In global warming potential analysis, different greenhouse gases are compared to CO2. For example, the global warming effect of 22,800 CO2 molecules is equivalent to effect of one SF6 molecule, because SF6 lasts longer in the atmosphere and absorbs radiation in a different wavelength. As a result, even small amounts of high GWP gases have a large impact on global warming (Air Quality Planning and Science Division, ARB, 2013).

The majority of statewide GHG emissions originate from fuel use activities, including transportation, electricity generation and heating. Fuel combustion is the largest contributor to statewide GHG emissions, constituting about 72 percent of overall emissions in 2012. Natural gas is the primary combustion fuel, mainly used for electricity generation, residential, commercial and industrial heating, followed by gasoline, which is consumed almost entirely by transportation sector.

Figure 22: California Greenhouse Gas Emission by Gas

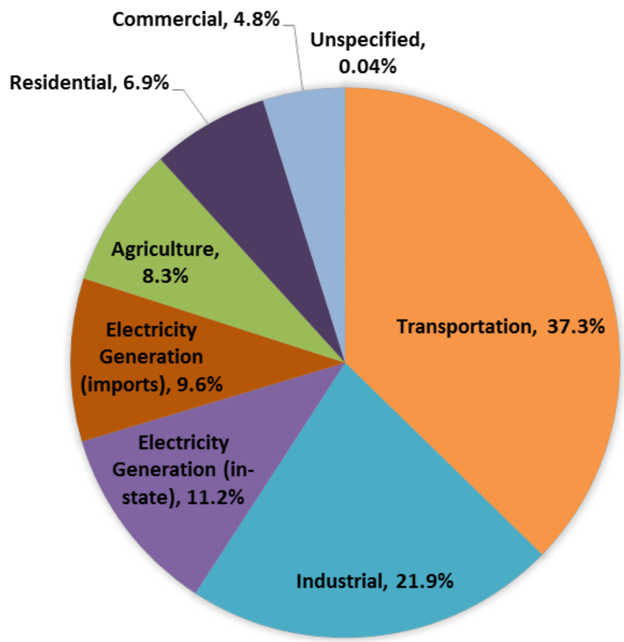


Source: (California Air Resources Board, 2014)

Figure 22 displays the percent contribution of each gas to the total 2012 California GHG emissions with CO2 being the largest contributor (86.5%). Methane (CH4) and nitrous oxide (N2O) accounted for 8.3 and 2.9 percent of the total statewide GHG emissions in 2012, respectively, while SF6 constituted about 0.1 percent of total emissions. Other halogenated gases contributed to 4 percent of total statewide GHG emissions.

Figure 23 illustrates the contribution of each economic sector to 2012 total statewide GHG emissions, with transportation being the largest contributor (36%), followed by industrial sector, the second largest, which accounts for 22 percent of the total GHG emissions. Electricity generation constitutes approximately 21 percent of the total emissions, with 11.2 percent in-state generation. The rest of GHG emissions were emitted by Agriculture (8.3%), residential (6.9%), and commercial (4.9%) sectors (California Air Resources Board, 2014).

Figure 23: 2012 California Greenhouse Gas Emissions by Economic Sector



Source: (California Air Resources Board, 2014)

In the following section, greenhouse gas emissions from each of the end-use sectors and their contributions to overall GHG emissions are discussed in detail.

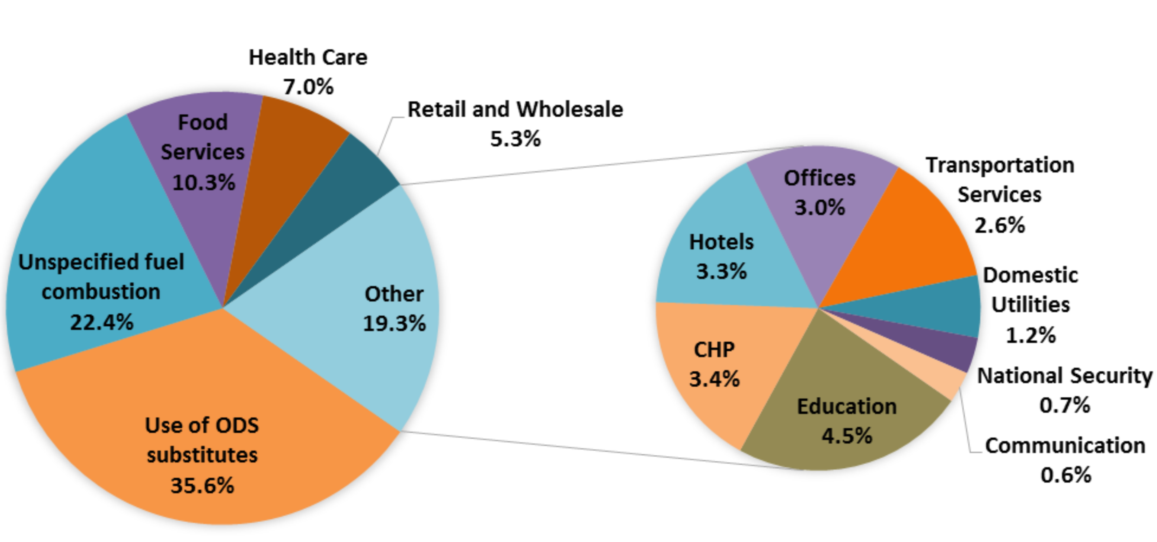
2.7.1.1 Residential Sector

The residential sector contributed to 6.9 percent of overall statewide GHG emissions in 2012. Carbon dioxide (CO2) was the primary greenhouse gas, which originated mainly from fossil fuel combustion. The majority of combustion-related emissions were attributed to burning of natural gas for activities including space heating, water heating, and cooking which constituted about 99 percent of total 2012 GHG emissions from residential sector.

2.7.1.2 Commercial Sector

In 2012, about 4.8 percent of the total statewide GHG emissions were emitted by the commercial sector. Figure 24 shows the percent contribution of each category to the overall GHG emissions. The use of ozone-depleting substances (ODS) alternatives had the largest contribution (35.5%) to overall GHG emissions from commercial sector. The unspecified fuel combustion was the second largest contributor, with emitting about 22% of total emissions. Natural gas was the primary fuel, which was mainly combusted for heating, and cooling purposes, as well as transmission through pipelines. Food services (10.3%) and healthcare (7%) were the next major contributors in the commercial sector.

Figure 24: 2012 GHG Emissions from Commercial Sector



Source: (California Air Resources Board, 2014)

The rest of GHG emissions were attributed to commercial activities including retail and wholesale, education, CHP, hotels, offices, transportation services, domestic utilities, national security, and communication.

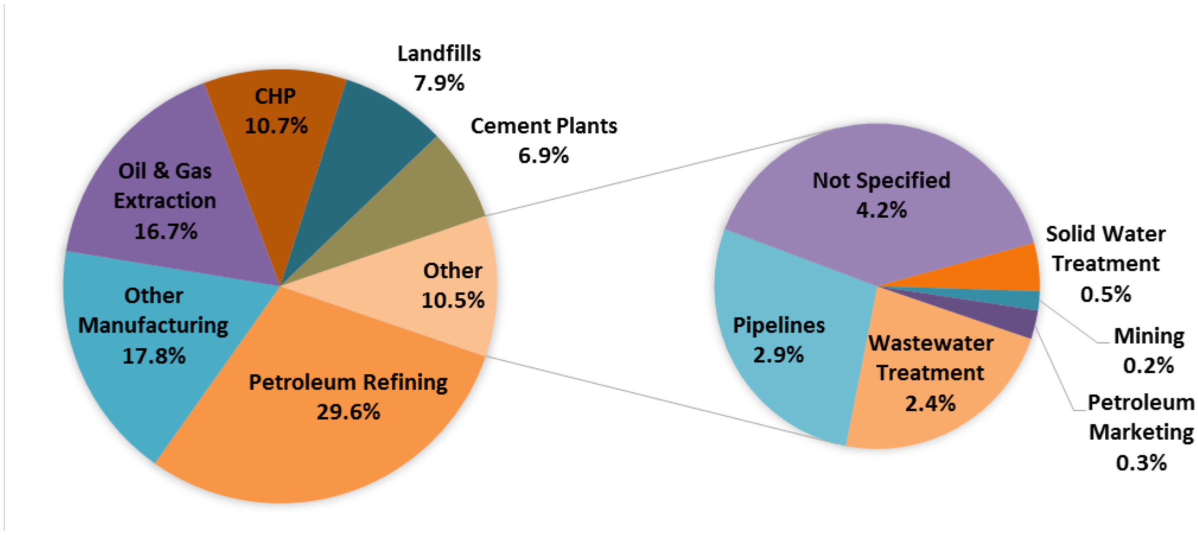
2.7.1.3 Industrial Sector

Industrial sector is a key source of GHG emissions with contributing to 23% of total U.S. emissions in 2012. However, this contribution increases to 28% when indirect and direct emissions from consumed electricity are considered (U.S. EPA, 2014).

GHG emissions emitted by industrial sector originate from (1) burning of fossil fuels for generating heat, power, and steam, (2) non-energy uses of fossil fuels (such as metal smelting and chemical processing), and (3) non-fossil fuel related processes (such as cement manufacture). Direct combustion of fossil fuels to generate steam and process heat is the main source of industrial GHG emissions. Moreover, emissions arise from by-products of chemical processes such as calcination in cement production. Such emissions constitute 5.1% of the 2012 U.S. total, with the substitution of ozone depleting substances such as hydrofluorocarbons representing the dominant source (U.S. EPA, 2014).

As Figure 25 illustrates, petroleum refining was the largest source of greenhouse gases, with emitting 30 percent of total industrial emissions in 2012. Roughly, 25 percent of industrial emissions were originated from manufacturing industries including cement production. CHP (10.7%) and landfills (7.9%) were the next two major contributors to Industrial emissions. The rest of GHG emissions were attributed to industrial activities including pipelines (2.9%), wastewater treatment (2.4%), solid waste treatment (0.5%), and Mining (0.2%).

Figure 25: 2012 GHG Emissions from Industrial Sector

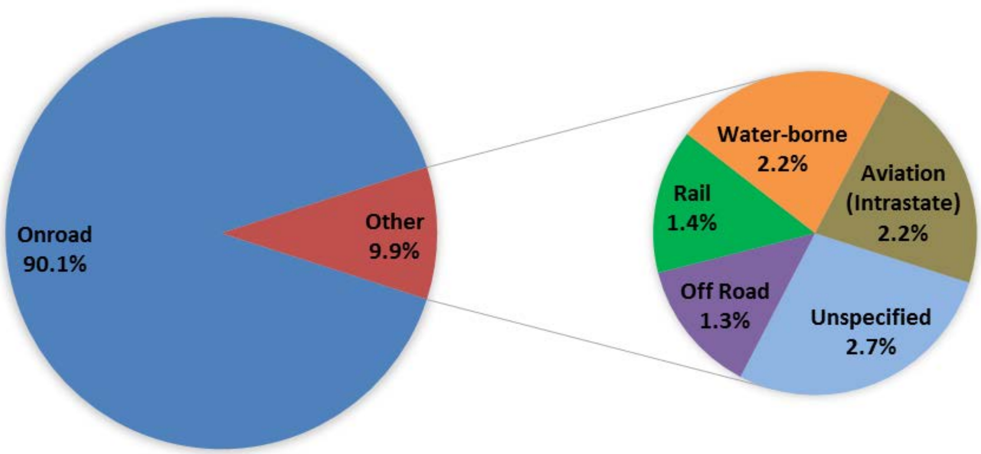


Source: (California Air Resources Board, 2014)

2.7.1.4 Transportation Sector

Transportation sector emitted 171 million tons of CO2 equivalent gross emissions in 2012, which accounted for 37.3 percent of the total statewide GHG emissions. These emissions originated from different transportation activities including on-road, off-road, water-borne, aviation, and railroad. Figure 26 displays the percent contribution of each transportation category to the overall transportation emissions in 2012. The on-road transportation is the main source of greenhouse gases, constituting 90 percent of emissions from this sector. This category contributes to more than 33 percent of total statewide GHG emissions, where more than 70% of these emissions arise from light duty vehicles.

Figure 26: 2012 GHG Emissions from Transportation Sector



Source: (California Air Resources Board, 2014)

2.7.2 Criteria Pollutants

Carbon monoxide (CO), sulfur dioxide (SO2), particulate matter (PM2.5 and PM10), and lead are identified by U.S. EPA as primary criteria pollutants, which are generated directly from the emission source. On the other hand, secondary criteria pollutants including ozone (O3) and nitrogen dioxide (NO2) are formed by chemical reactions of forerunner emissions in the atmosphere. For example, ozone (O3) is formed when nitrogen oxides (NOx) and volatile organic compounds (VOC) react in the presence of ultraviolet radiation in the atmosphere. PM2.5 and PM10, known as particulate matter, are complex pollutant that can be either directly emitted or indirectly formed in the atmosphere by chemical reaction of forerunner emissions including NOx, Sox, VOC, and NH3. Dust and soot are the most common examples of directly emitted particulate matter (Air Quality Planning and Science Division, ARB, 2013). In the following section, each criteria pollutant is discussed in detail.

2.7.2.1 Ozone

Ozone is the key element of urban smog, which is not directly emitted, but is formed in the atmosphere when forerunner emissions, including NOx and VOC, react in the presence of solar radiation. The optimum condition for ozone formation is comprised of stagnant air and warm temperatures, which makes summer the peak ozone season. The peak ozone concentrations often occur far downwind of forerunner emissions due to the reaction time which results in affecting a large area.

Ozone is highly reactive and destructive to living cells, such as those existing in human lungs. Inflammation and irritation of the tissues of respiratory system are the main symptoms of exposure to high concentrations of ozone, which disturb airflow through the lungs and cause shortness of breath. Frequent exposure to sufficient dozes of ozone results in chronic health effects including reduced lung function and asthma. In 2005, California Air Resources Board regulated an eight-hour standard of 0.07 ppm for ozone and maintained the one-hour standard of 0.09 ppm, which was established in 1987 (Air Resources Board, 2008).

2.7.2.2 Particulate Matter

PM is comprised of various substances ranging from elements, such as carbon and metals, to compounds, such as sulfates, nitrates, and organic compounds, to complex mixtures, such as soot and dust. While some of these particles are emitted directly, others are formed through physical and chemical reaction of primary emissions in the atmosphere and referred to as secondary particles. Primary particulate matter arise mainly from combustion activities (transportation, electric generation, heating, cooking, etc.), and certain industrial processes, such as crushing or grinding operations.

Particulate matter includes all particles with a diameter of 10 microns or smaller (PM10), while PM2.5 is a subclass of finer particles with a diameter of 2.5 microns or smaller (PM2.5), which cannot be caught by upper respiratory tract and can penetrate deep in the human lungs, posing an increased health risk (Air Quality Planning and Science Division, ARB, 2013). Lung disease, respiratory infections, asthma and acute bronchitis are the major consequences of long-term exposures to PM (Arizona Department of Environemtnal Quality, n.d.).

The State of California has established and enforced the annual standards of 20 μg/m3 and 12 μg/m3 for PM10 and PM2.5, respectively, which indicate the maximum concentration of particulate matter that can exist in atmosphere without causing serious health risks (Air Resources Board, 2009).

2.7.2.3 Carbon Monoxide

Carbon Monoxide is directly emitted due to incomplete combustion of certain fuels, such as gasoline and wood, from various sources. The peak CO concentrations occur in winter because of the optimum conditions including cold temperature and low-wind weather. Long-term exposure to high concentrations of CO can cause heart disease, lung disease, and impairment of nervous system functions. Since 1989, ARB has retained the eight-hour standard of 9 ppm and one-hour standard of 20 ppm for CO (Air Resources Board, 2009).

2.7.2.4 Nitrogen Dioxide

Nitrogen dioxide (NO2) is one of the unstable and highly reactive gases known as Nitrogen Oxides (NOx) which originate mainly from high-temperature combustion of fossil fuels. NO2 is indirectly formed in the atmosphere by a series of complex reactions between ozone, NOx, and other pollutants in presence of sunlight. Residential fuel burning activities including heating and cooking processes generate significant amounts of NO2. Lung disease and impairment of respiratory functions are the major consequence of long-term exposure to sufficient dozes of NO2. The 1-hour standard of 0.18 ppm and annual standard of 0.03 ppm for NO2 has been established and enforced by California ARB.

2.7.2.5 Sulfur Dioxide

Sulfur dioxide (SO2) is one of a group of reactive and oxidizing gaseous compounds known as Sulfur Oxides (SOx) which arise mainly from combustion of petroleum-refined fuels, such as gasoline and diesel that contain sulfur. In addition, certain industrial processes, such as petroleum refining and metal processing emit substantial amounts of SO2. Exposure to high concentrations of SO2 has adverse health effects including chronic lung disease, cardiovascular disease, and impaired respiratory functioning. The current 1-hour standard of 0.04 ppm for SO2 was adopted in 1991 by California ARB.

2.8 Electrification

Under the Energy Policy Act of 1992, electricity is considered an alternative fuel. In order to achieve the California emissions reduction goals, improving energy efficiency and decarbonizing energy sources may not be sufficient alone. Hence, electrification is considered as a technically feasible way to boost the reduction of emissions. Electrification is the implementation of electric-powered devices in place of fuel-supplied ones. Doing so results in an increased electricity demand load while additionally reducing distributed production of GHG and air pollutant emissions due to burning fossil fuels.

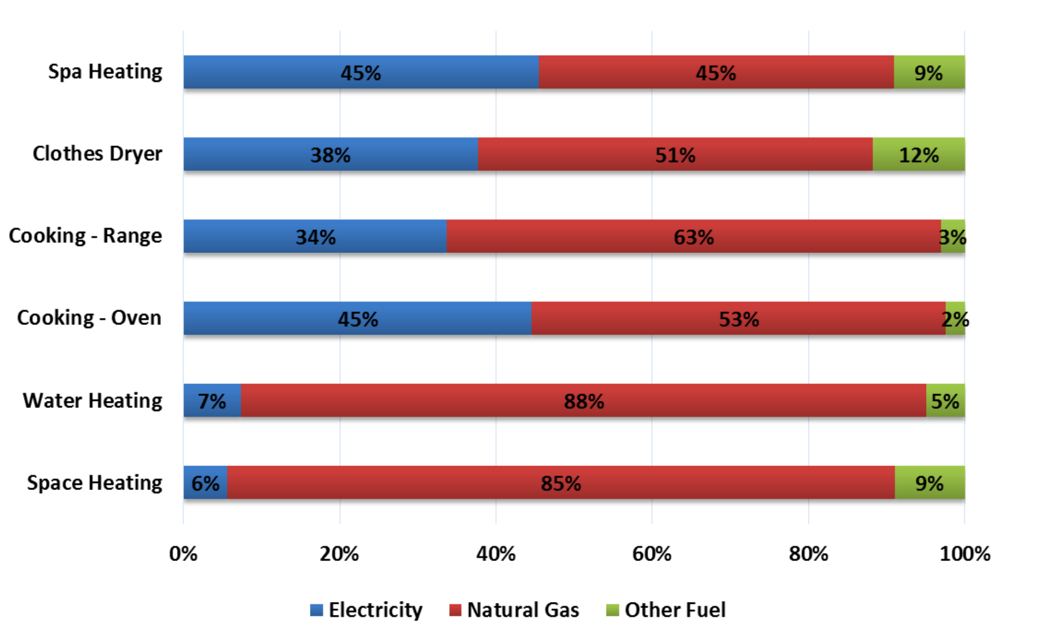
2.8.1 Electrification Potential

In this section, the energy consumption of primary energy end uses are break down by fuel type and their current electric penetrations are estimated and discussed in order to evaluate the potential of implementing electrification.

2.8.1.1 Residential Sector

As we discussed in section 0, about 44 percent of total residential energy use is associated with appliances, electronics and lighting, which are mainly powered by electricity. Contrary natural gas is the dominant fuel in other residential end uses with powering more than half of their total energy demand (KEMA Inc., 2010). As Figure 27 illustrates, less than seven percent of total residential heating demand is supplied by electric power, while natural gas make up a much larger portion with constituting 85 percent of space heating and 88 percent of water heating energy demands. Electricity is more widespread in other residential end-uses, for example, 34 to 45 percent of total cooking energy demand is met by electricity. Other residential end uses, with diverse fuel use, include clothes dryer and spa heating where electric power account for 38% and 45% of their overall energy use, respectively. Low electric penetration of high-energy consuming residential end uses, including space heating, water heating and cooking, demonstrate great potential of residential sector for implementing electrification.

Figure 27: Electric Penetration of California Residential End-Uses in 2009

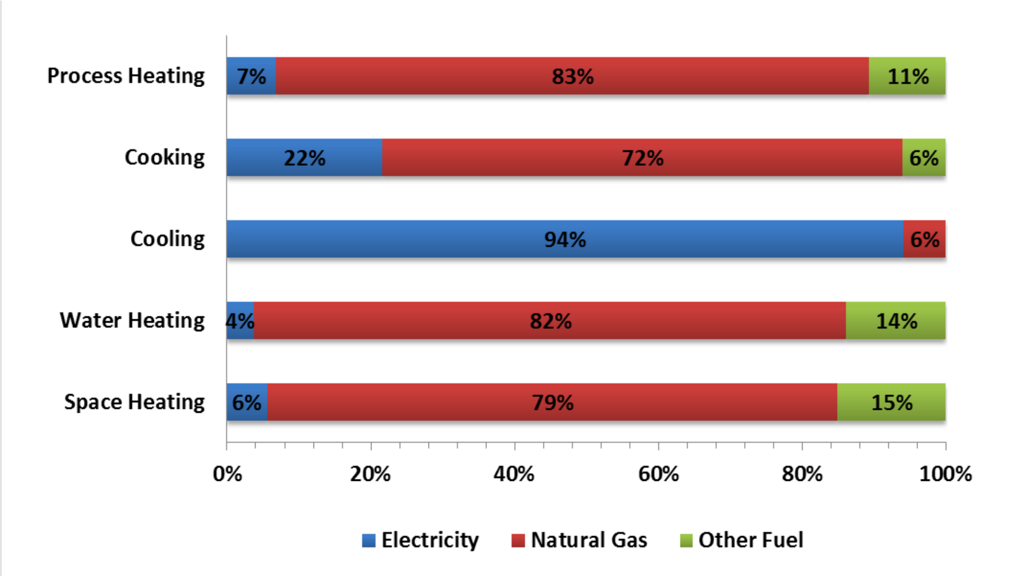


Source: (KEMA Inc., 2010)

2.8.1.2 Commercial

Similar to residential sector, commercial sector can be classified into two categories: (1) pure-electric end uses, such as refrigeration and lighting, which run on electric power completely (2) diverse-fuel end uses, such as heating and cooking that are powered by various types of fuel. Figure 28 displays the contribution of different fuels to the total energy consumption of diverse-fuel end uses in 2006. Electricity is not extensively used for heating activities including space heating (6%), water heating (4%) and process heating (7%), while it supplies roughly 94 percent of cooling energy demand. In addition, natural gas is the primary fuel used for commercial cooking, while electricity constitutes only 22 percent of cooking energy demand.

Figure 28: Electric Penetration of California Commercial End-Uses in 2006



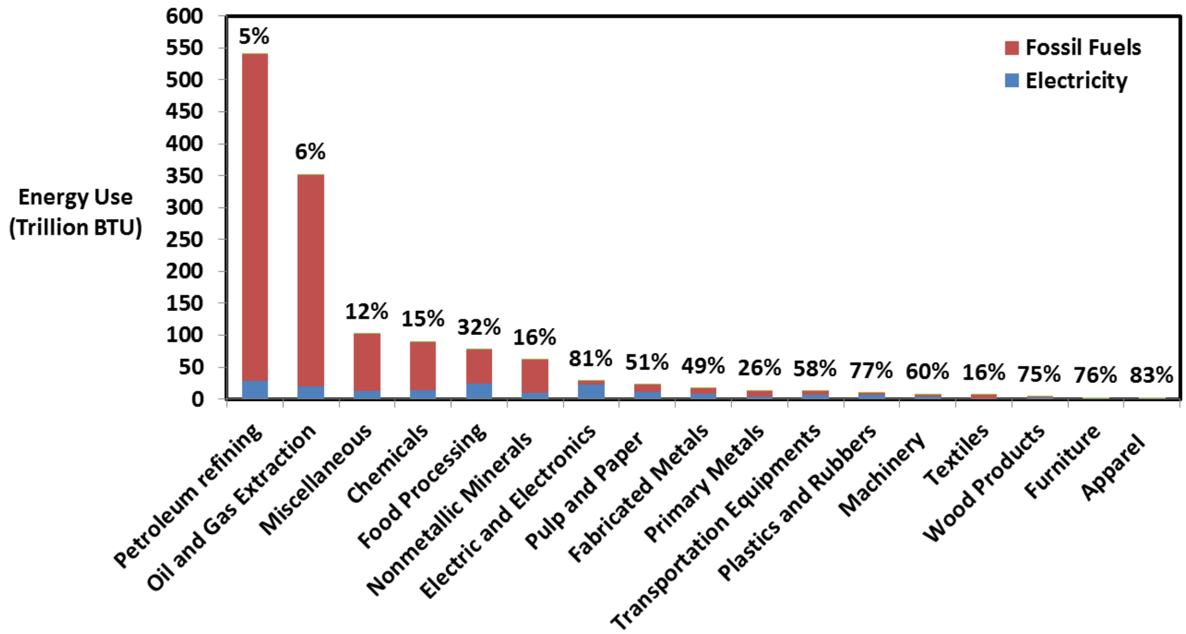
Source: (Itron Inc., 2006)

2.8.1.3 Industrial

Currently most of the energy required for powering industrial sector is supplied by fossil fuels including petroleum (27%), natural gas (26%) and coal (6%). The remaining energy need is delivered by electricity, which represents roughly a third of sector consumption.

Figure 29 compares electricity and fossil fuels consumed by various California industries in 2008 (California Energy Commission, 2010). In this figure, the industries are in ascending order of electric penetration from left to right; the petroleum refining industry has the lowest electric penetration (5.22%), and apparel manufacturing has the highest (83.09%). As this figure shows, most of the energy need of energy-intensive industries, including petroleum refining, oil/gas extraction, chemical manufacturing, etc., is provided by fuels other than electricity. About 80% of total industrial energy use is consumed by industries with electric penetrations less than 15% (Figure 2-29) which indicates the great potential for implementing electrification in the industrial sector.

Figure 29: Energy Use of California Industry Subsectors, 2008



Source: (California Energy Commission, 2010)

Due to the complexity of energy consumption and associated environmental impacts, industrial sector represents one of the most challenging end-use sectors to study (Greening, et al., 2007). However, it is clear that extensive enforcement of mitigation strategies in the industrial sector can lead to significant GHG reductions.

2.8.1.4 Transportation

Transportation is one of the most diverse end-use energy sectors with ranging from light-duty passenger vehicles to international shipping to air transportation. In 2013, about 63 percent of total U.S. transportation energy consumption was attributed to light-duty vehicles, but this number is projected to fall below 51 percent in 2040 mainly due to improvements in vehicle fuel efficiency (U.S. EIA, 2014).

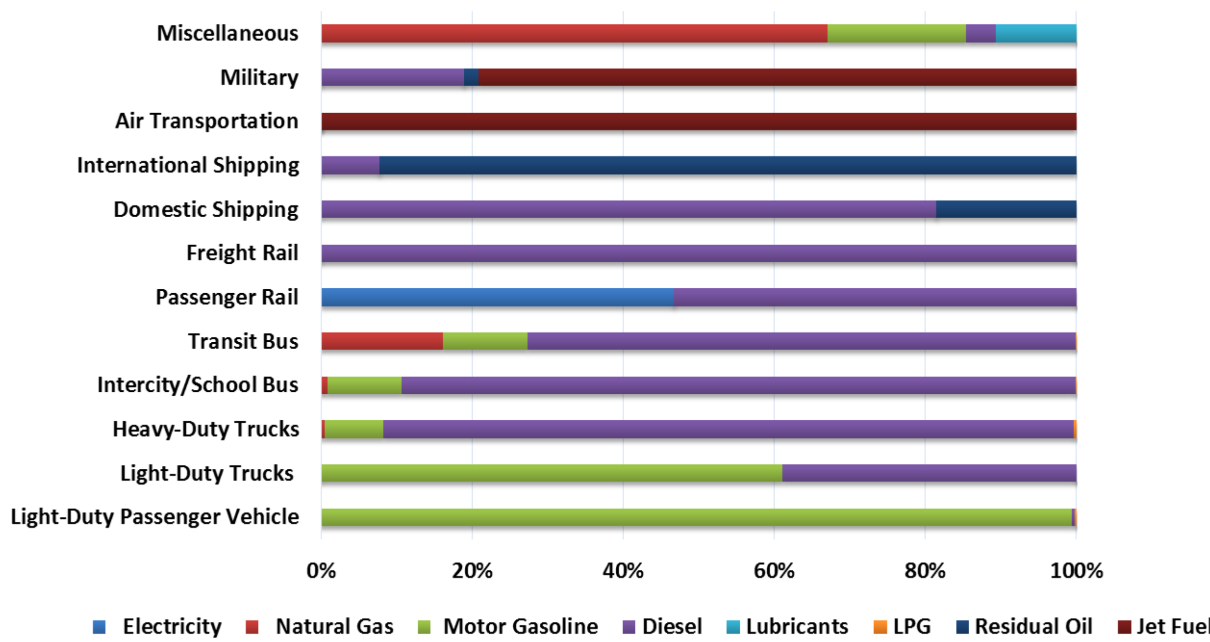
Figure 30 breaks down the energy consumption of different transportation modes by fuel type in 2013. More than 99 percent of light-duty passenger vehicles are powered by motor gasoline, while electricity makes up only 0.02 percent of their total energy consumption. Comparing to light-duty passenger vehicles, light- and heavy-duty trucks are less dependent on gasoline since distillate fuel oil (diesel) delivers 40 percent and 91 percent of their total energy demand, respectively. Although electricity has a negligible contribution to energy consumption of heavy-duty trucks, about 1 percent of the mode's overall energy use is attributed to other alternative fuels including liquefied natural gas (LNG) and liquefied petroleum gas (LPG). Diesel is the main fuel powering intercity and transit buses with delivering about 89 percent and 72 percent of their total energy demand, respectively. Approximately 10 percent of the overall energy consumption of buses is attributed to motor gasoline, while the rest is supplied by natural gas.

In contrast to other modes of transportation, which have negligible electric penetration, passenger rail is highly reliant on electricity with supplying 47 percent of its total energy need from electric power. On the other hand, the total energy demand of freight rail is delivered by diesel fuel.

Residual fuel oil and diesel are the primary fuels propelling non-recreational marine transportation, including domestic and international shipping; about 19 percent of domestic shipping and 92 percent of international shipping are powered by residual fuel oil, while the rest of their energy demand is supplied by diesel.

Jet fuel supplies the total energy demand of air transportation, while it delivers 79 percent of the overall military energy use. The remaining energy need of military transportation is supplied by diesel (19%) and residual fuel oil (2%).

Figure 30: Detailed Breakdown of U.S. Transportation Energy Use by Fuel, 2013



Source: (U.S. EIA, 2014)

Light-duty passenger vehicles and passenger rail are the only modes of transportation that have deployed electricity as an alternative fuel. Low electric penetration, high contribution to the overall GHG emissions, and availability of advanced electric-drive technologies are the key reasons to consider light-duty vehicles as the mode with highest potential for implementing electrification. Although electrification of heavy-duty vehicles, buses and railways might be possible in near future, electrification of other transportation modes including air and marine is not feasible due to energy storage and power density limitations.

2.8.2 Electrification Technologies

In this section, we present some of the available electric technologies that can be utilized for implementing electrification. Since residential and commercial sectors are similar, their electrification technologies are presented in one section.

2.8.2.1 Residential and Commercial

Electric Space Heating

Resistance Heating: Electric resistance heating converts nearly 100% of the energy in the electricity to heat by passing electric current through a thermal-resistant element. The heat can be generated by centralized forced-air furnaces or by regional heaters in each room, both of which include a variety of heater types including electric radiant heaters, electric space heaters, and electric furnaces.

Heat Pump: Heat pumps provide heat by transferring thermal energy from a cold medium to a warmer one, thus maintaining the heated space at high temperatures. Heat pumps are intended to transfer energy in reverse direction of spontaneous heat flow by absorbing heat from a low-temperature space and discharging it to a high-temperature one. Some amount of external electric power is required to accomplish heat transfer between two media. Heat pumps have their optimum performance in climates with moderate heating and cooling demands.

Electric Water Heating

Resistance Heating: Electric resistance water heater provides heat by using a thermal-resistant element carrying alternating current. The resistance of the element to the flow of electric current generates heat that warms up water.

Heat Pump: Heat pump water heater use electric power to transfer heat from a cold place to another instead of generating heat directly. Hence, they can be more energy efficient than conventional electric resistance water heaters. This system absorbs heat from surrounding air and transfers it to water in an enclosed tank. There are two types of heat pump available in the market: 1) air-source heat pump that uses outdoor air as the heat source 2) ground-source (geothermal) heat pumps, which pull thermal energy from the ground during winter. Although geothermal heat pumps cost more to install, they can achieve higher efficiencies compared to air-source heat pumps, hence their operating costs are lower.

Electric Cooking

Electric Resistance Oven: Electric resistance oven operate by using a heating element, which is simply a big resistor wire, with adequate resistance to generate a sufficient amount of heat. Typically, the heating element is Nichrome wire with ceramic insulation, which is surrounded by a steel sheath.

Electric Resistance Stove: An electric stove, also known as range or cooktop, is a stove that generates heat by converting electrical energy into thermal energy for cooking. In electric stoves, the heater elements are configured in a round-shape surface unit, which is comprised of a few elements all mounted together, with diverse resistance ratings.

Electric Induction Cooktop: Induction cooktops accomplish cooking by electromagnetic induction, instead of electrical heating element. Almost all types of induction cooktops include a cooking vessel, which is made out of a ferromagnetic metal such as stainless steel or cast iron. In an induction cooker, an alternating current is passed through a copper coil, which creates an oscillating magnetic field. The magnetic flux generates an eddy current in the ferrous pot, which converts the electrical energy into heat. Faster heating, enhanced thermal efficiency, and precise controllability are some of the advantages of induction cooking.

Crockpot: Crockpot, also known as slow cooker, is an electrical cooking appliance that maintains the cooking temperature relatively low. A crockpot is comprised of an oval pot, made of ceramic or porcelain, surrounded by a metal manifold, which contains a thermal-resistant heating element.

Microwave Oven: A microwave oven is an electric appliance that cooks by bombarding food with electromagnetic radiation in the microwave wavelength range, resulting in rotation of polarized food molecules and accumulation of thermal energy in a dielectric heating process. The benefits of microwave ovens are quick and uniform cooking as well as high thermal efficiency.

2.8.2.2 Industrial

Electricity can be used as the main energy source in three industrial phenomena including electromotive, electrolytic, and electrothermal, while the latter is the only one suppressed by fossil-fuel thermal technologies. Since electromotive and electrolytic processes are pure electric, we only consider electrothermal phenomenon for implementing electrification.

Industrial electrothermal technologies, which are industrial technologies that use electricity to manufacture products by means of heat, can meet pressure, temperature, and capacity requirements of many industrial processes. These technologies have superior efficiency at rated capacity and across lower ranges of capacity. Design and integration is one of the key issues with regard to industrial electrification; although integration of electro-technologies might be challenging for complicated industries (such as petroleum refining), simpler industries such as food processing would need much less integration requirements.

Technically electrical processing can deliver unlimited energy density and accurate controllability. In several cases, synergistic combination of effects may lead to shortcut manufacturing steps. In addition, there is no thermodynamic limit on the temperature in electrothermal process. Arc-produced plasmas can achieve temperatures as high as 10,000°F (5538°C) while industrial combustion processes are limited to the adiabatic flame temperature, a theoretical limit of about 3000°F (1649°C) for typical industrial fuels burned in air (SCHMIDT, 1987).

In electric-based process heating systems, heat is generated from electric current or electromagnetic fields. Direct heating methods operate by either (1) passing an electrical current through the material, (2) inducing an electrical current (eddy current) into the material, or (3) exciting atoms and/or molecules within the material with electromagnetic radiation (like in a microwave). Indirect heating techniques use one of these three approaches for generating heat, and then transferring it to the material by single or multiple modes of heat transfer including conduction, convection, and radiation (Lawrence Berkeley National Laboratory, 2007).

Many manufacturing industries use process heating for a wide range of applications, which often consist of multiple heating processes. A summary of industrial processes, their applications, equipment, and industries where these processes are commonly used, are presented in Table 1: Summary of Process Heating Operations.

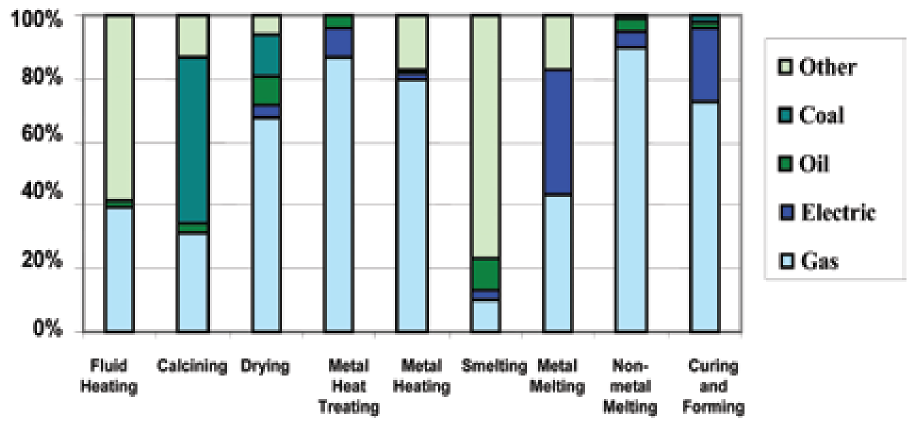
Table 1: Summary of Process Heating Operations

Process	Application	Equipment	Industry
Agglomeration—Sintering	Metals Production	Various Furnace Types, Kilns, Microwave	Primary Metals
Calcining	Lime Calcining	Various Furnace Types	Cement, Wallboard, Pulp and Paper Manufacturing, Primary Metals
Curing and Forming	Coating, Polymer Production, Enameling	Various Furnace Types, Ovens, Kilns, Lehrs, Infrared, UV, Electron Beam, Induction	Ceramics, Stone, Glass, Primary Metals, Chemicals, Plastics and Rubber
Drying	Water and Organic Compound Removal	Fuel-Based Dryers, Infrared, Resistance, Microwave, Radio-Frequency	Stone, Clay, Petroleum Refining, Agricultural and Food, Pulp and Paper, Textile
Forming	Extrusion, Molding	Various Ovens and Furnaces	Rubber, Plastics, Glass
Fluid Heating	Food Preparation, Chemical Production, Reforming, Distillation, Cracking, Hydrotreating, Visbreaking	Various Furnace Types, Reactors, Resistance Heaters. Microwave, Infrared, Fuel-based Fluid Heaters, Immersion Heaters	Agricultural and Food, Chemical Manufacturing, Petroleum Refining
Heating and Melting—High-Temperature	Casting, Steelmaking, Glass Production	Fuel-Based Furnaces, Kilns, Reactors, Direct Arc, Induction, Plasma, Resistance	Primary Metals, Glass
Heating and Melting—Low-Temperature	Softening, Liquefying, Warming	Ovens, Infrared, Microwave, Resistance	Plastics, Rubber, Food, Chemicals
Heat Treating	Hardening, Annealing, Tempering	Various Fuel-Based Furnace Types, Ovens, Kilns, Lehrs, Laser, Resistance, Induction, Electron Beam	Primary Metals, Fabricated Metal Products, Glass, Ceramics
Incineration/Thermal Oxidation	Waste Handling/Disposal	Incinerators, Thermal Oxidizers, Resistance, Plasma	Fabricated Metals, Food, Plastics and Rubber, Chemicals
Metals Reheating	Forging, Rolling, Extruding, Annealing, Galvanizing, Coating, Joining	Various Furnace Types, Ovens, Kilns, Heaters, Reactors, Induction, Infrared	Primary Metals, Fabricated Metal Products
Separating	Air Separation, Refining, Chemical Cracking	Distillation, Membranes, Filter Presses	Chemicals
Smelting	Steelmaking and Other Metals (e.g., Silver)	Various Furnace Types	Primary Metals
Other Heating Processes	Food Production (including Baking, Roasting, and Frying), Sterilization, Chemical Production	Various Furnace Types, Ovens, Reactors, and Resistance Heaters. Microwave, Steam, Induction, Infrared	Agricultural and Food, Glass, Ceramics, Plastics and Rubber, Chemicals

Source: (Lawrence Berkeley National Laboratory, 2007)

Availability, cost, compatibility and efficiency are the key factors in choosing the energy source for process heating systems. Figure 31 shows the share of different energy sources in process heating applications.

Figure 31: Share of Different Fuels in Industrial Process Heating



Source: (Lawrence Berkeley National Laboratory, 2007)

In the following, a brief description of commercialized electro-thermal technologies are presented.

Arc Furnaces

Arc furnaces heat materials using an electric arc. The application of this systems range from casting industry as small as 1-ton capacity for producing cast iron products, to units as large as 400 tons used for manufacturing steel from scrap iron. Induction arc furnaces can be used for numerous metal melting applications. The same processes are implemented by Induction arc furnaces as various types of fuel-based furnaces.

Electric Infrared

Electric infrared systems generate heat through emitting infrared radiation as a result of passing electrical current through a solid resistor. Precise temperature controllability is the key feature of these systems, which is essential for surface treatment, cure coating, and material drying applications. Infrared heating can also be used in bulk heating applications such as booster ovens.

Electron Beam

Electron beam heating system use a focused and directed beam of electrons to heat the work piece. Many industries including automotive industry use electron beam heating for welding in extensive volume. Electron beam is recently used for surface treatment applications especially local surface hardening of high-wear components.

Induction heating

Induction systems generate heat by passing electromagnetic fields through conductive materials. The electromagnetic field induces eddy current in the work piece and then generates heat by interacting with the material resistance.

Direct induction: Direct induction heating occurs when the material is directly exposed to electromagnetic field. It is possible to achieve high power densities and high heating rates by using direct induction heating systems. These systems are widely used in metals industry for melting and heat treatment applications.

Indirect induction: An eddy current is induced through a conductive material as a result of electromagnetic field generated by a susceptor, which is in contact with the work piece for processing. Indirect induction heating is extensively used for melting optical glasses in platinum crucibles.

<u>Laser</u>

The surface of a material is rapidly heated by laser beam to create a hardened layer. The shape, direction and power output of laser beam can be precisely controlled. Localized hardening of metal parts is the most familiar application of laser heat processing.

<u>Microwave</u>

Microwave heating systems heat the material by means of electromagnetic radiation, which incites water molecules in the material, or generates heat in a susceptor. Textile and polymer drying, food processing, and sintering of ceramics are the most familiar applications of microwave heat processing.

<u>Plasma</u>

Plasma is generated by drawing electric arc between two electrodes, which yields heating, and partially ionizing a continuous stream of gas. Industrial and extractive metallurgy, surface treatments such as coating, etching in microelectronics, metal cutting and welding are the most common applications of plasma heat processing.

<u>Radio Frequency</u>

Similar to microwave heating, radio frequency system generates heat to dry moisture in nonmetallic materials by means of high-frequency electromagnetic radiation. However, the longer wavelength of radio enables them to heat larger volume of materials more efficiently than microwave heating. Radio frequency heat processing is extensively used in food processing applications as well as drying of textiles, ceramics and polymers.

<u>Resistance heating</u>

Direct Resistance Heating: Heat is generated by passing an electric current through a conductive material, resulting in a temperature rise. Melting of glass and metal are the applications of direct resistance heating.

Indirect Resistance Heating: *In these* systems, heat is generated by passing electrical current through a resistor, and then transmitted to the material by convection and/or radiation.

<u>Ultraviolet Curing</u>

A photochemical process is initiated by using UV radiation to transmute liquid polymers into a rigid, solid film. Protective and decorative coatings, laminations, electronics, and printing are the most common applications of ultraviolet curing.

Electric Boiler

In electric boilers, most of the heat content of steam is stored as latent heat; hence, large quantities of heat can be transferred efficiently at a constant temperature, which is a useful attribute in many process-heating applications. Electric boilers are classified into two categories based on the method used for steam generation.

Resistance Heating: Steam is generated by passing electrical current through a thermal-resistant metal element that is immersed in water. The element resists the flow of current and dissipates heat, which is then transferred to water by conduction and convection and finally steam is generated.

Electrode Heating: In this method, water itself is utilized as the thermal-resistant element carrying alternating current between metal electrodes. The resistance of the water to the flow of current generates heat that results in quick steam generation. Higher heat transfer efficiency, superior controllability, minimal space and piping requirements are some of the advantages of electrode heating electric boilers.

2.8.2.3 Transportation

There are some challenges associated with electrification of transportation sector including, but not limited to, EV ownership cost, driving range, and charging infrastructure. Although the capital cost of electric vehicles is higher, their operating costs are lower. Currently there are two electric-drive technologies available in the market for electrifying light-duty passenger vehicles:

Plug-in Hybrid Electric Vehicles (PHEVs)

PHEVs are propelled by both internal combustion engine and electric motor, which can operate in either series or parallel configuration. The electric motor is powered by a battery pack that can be recharged by regenerative breaking as well as external power source. PHEVs relieve the range concern associated with battery electric vehicles, since the internal combustion engine performs as a backup when the batteries are depleted; this leads to high driving ranges comparable to fossil-fueled ICE vehicles.

Battery Electric Vehicles (BEVs)

BEVs, also known as all-electric vehicle, have only electric motor for propulsion. Similar to PHEV, the electric motor derives all its power from the battery pack and thus has no internal combustion engine. The battery pack is recharged by either regenerative breaking or external power source.

CHAPTER 3: Methodology

In this chapter, the required steps for achieving the goals and objectives of this study are described in detail.

3.1 Scenario Development

This section details the development of implementation scenarios for electrification of end-use energy sectors in 2020, 2030, and 2050. Before developing the electrification scenarios for each year, business-as-usual approach is employed to define a base-case scenario, which is used as a reference for comparing the emission and air quality impacts.

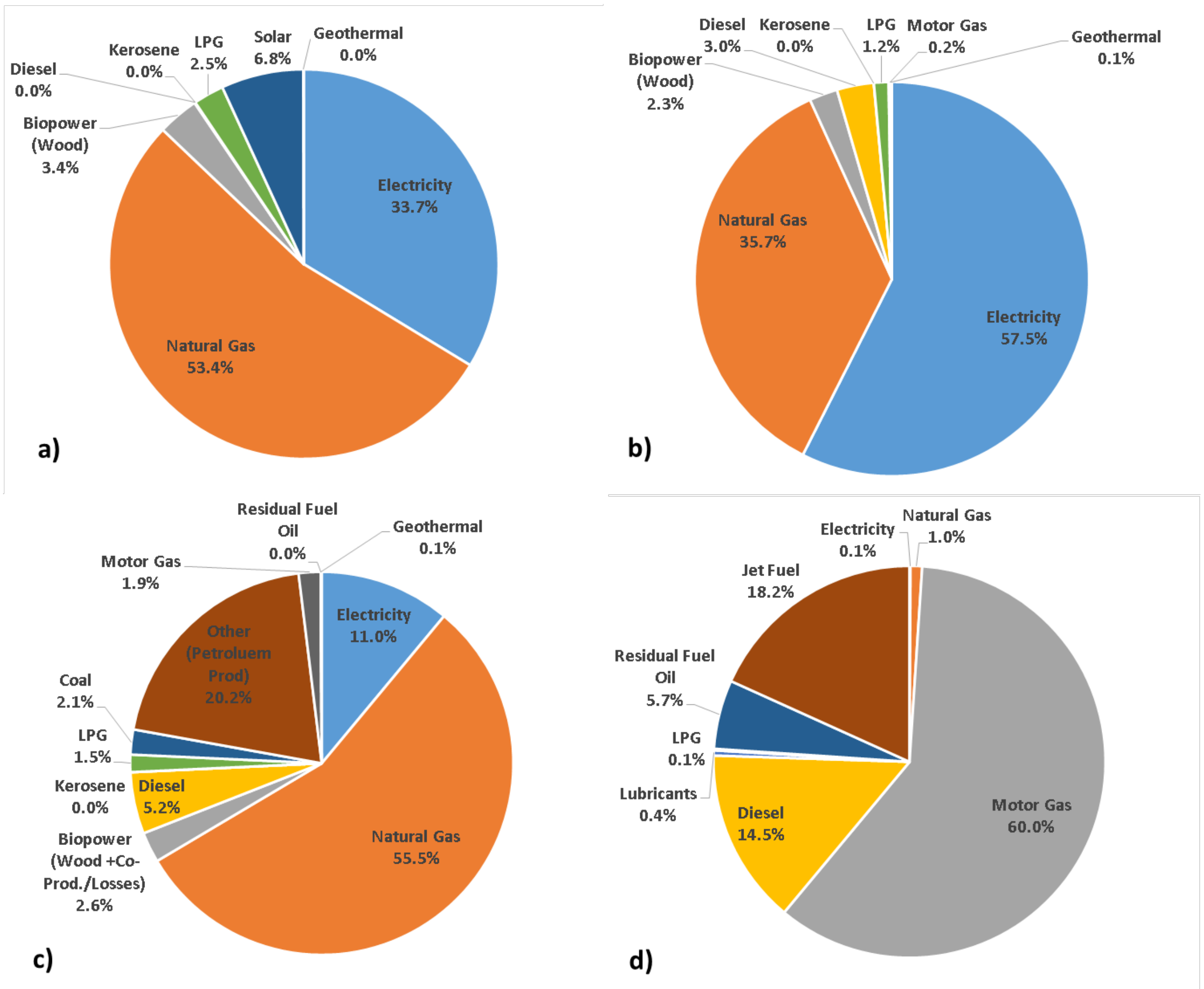
3.1.1 Development of Business-As-Usual Scenarios

For developing implementation scenarios, the electrification potential of each end-use sector is determined based on the projected electric penetration, which is obtained by estimating the energy consumption of each sector using MARKAL projection data. The 2012 energy consumption estimates are used as the base case for projecting energy consumption of California in 2020, 2030 and 2050. From these BAU cases, we can perceive the fuel consumption distribution and determine which sectors and fuels reflect electrification potential. Therefore, the most recent EIA California energy consumption data is organized by sector and source, and then compared directly to U.S. sector consumption estimates generated by MARKAL.

Figure 32 shows that almost one third of total residential energy use of California is in form of electricity. A small percentage of total residential energy is supplied by biomass and petroleum. Natural gas is the main fuel consumed in residential buildings, providing 53.4 percent of total energy. As can be seen in Figure 3-1b, natural gas is again a prominent fuel, but with 35.7 percent usage, is less than electricity with 57.5 percent. Similar to residential buildings, a small percentage of total energy consumption of commercial buildings is from petroleum and biomass.

Figure 3-1c indicates that only 11 percent of total energy need of industrial sector is supplied by electricity. Natural gas and petroleum are the main fuels consumed in industrial sector supplying about 55.5 percent and 27 percent of total energy use respectively. Lastly, as we could expect, transportation has the lowest electric penetration amongst all sectors contributing to only 0.1 percent of its total energy use. As Figure 3-1d shows, gasoline is the main fuel consumed in transportation sector with supplying about 60 percent of total energy use.

Figure 32: 2012 End-Use Energy Consumption Estimates in California



a) Residential b) Commercial c) Industrial d) Transportation

Source: (U.S. Energy Information Administration, 2012)

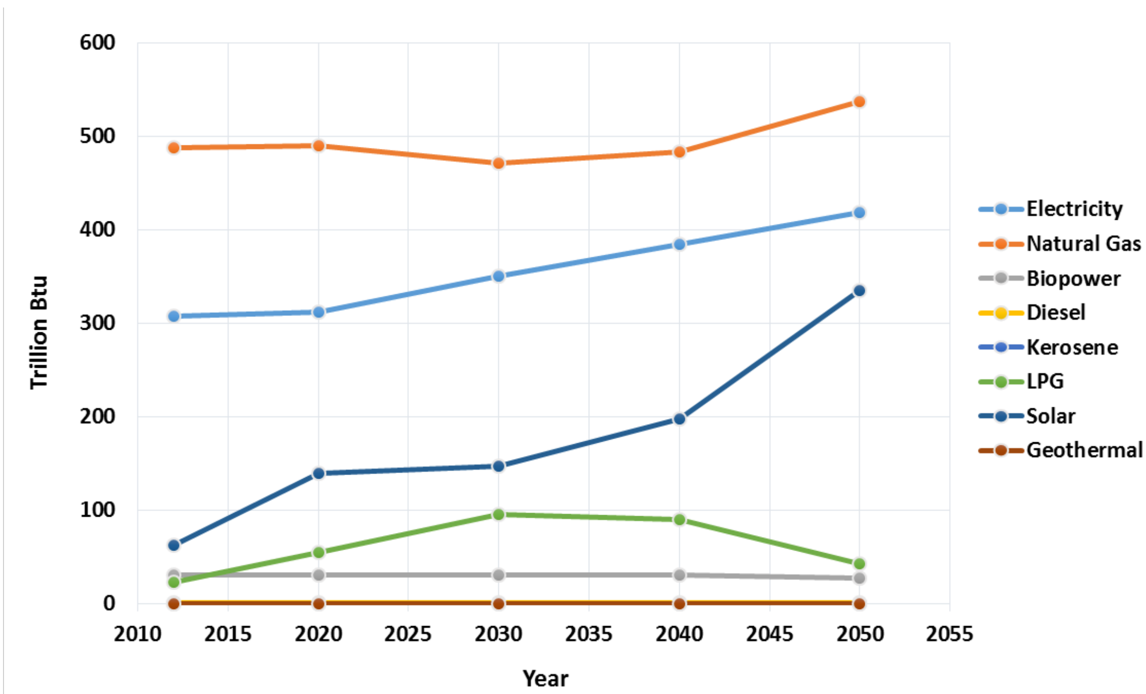
3.1.1.1 MARKAL Projections by Fuel

The MARKet ALlocation (MARKAL) model is a regional energy system optimization model, which delivers a technology-based foundation for projecting energy trends over a specified time horizon (Fishbone & Abilock, 1981) (Loulou, et al., 2004) (Rafaj, et al., 2005). MARKAL characterizes energy production and consumptions as well as existing and projected technologies required for balancing energy demands. MARKAL optimizes technology and fuel investments, allocating market shares in order to minimize overall energy costs while meeting the modeled constraints. Model inputs such as existing stock of energy-related technologies are adjusted to characterize a specific scenario, providing insights into future technologies, primary energy sources, and emissions. For analyzing the business-as-usual scenarios with MARKAL, a database developed by US EPA (US Environmental Protection Agency, 2006) is used. This database represents the US energy system including resource supply, electric power generation, and end-use energy consumption at the national and regional levels, over a time horizon from 2000 through 2050.

To establish projections for the years 2020, 2030, and 2050, it is necessary to have a direct comparison to the reference (2012) data. In the first step, 2012 U.S. energy consumption estimate was determined through interpolation of MARKAL data, which is available for years 2005, 2010 and 2015 (Loughlin, et al., 2011). Then the change from the 2012 to the MARKAL projected 2020, 2030, and 2050 values are calculated and then divided by the lower year and expressed as a decimal. This decimal difference is then applied to the CA values to create projected values for their respective sources and sectors. There are significant increases in natural gas consumption estimates because the version of MARKAL used for comparison was calibrated to the U.S. EIA's Annual Energy Outlook Reference case from 2010, which utilized natural gas usage due to the natural gas boom.

Figure 33 through Figure 36 show the energy consumption projections by fuel for each end-use energy sector. From 2040 to 2050, the contribution of solar energy to total residential energy demand increase substantially, as the cost of solar technologies shrink. In addition, State programs, utility programs, and Federal tax rebates boost distributed solar PV generation applications.

Figure 33: California Residential Energy Consumption Projections by Fuel



As Figure 34 illustrates, commercial natural gas and electricity consumption continue to grow due to increasing demand caused by economic growth.

Figure 34: California Commercial Energy Consumption Projections by Fuel

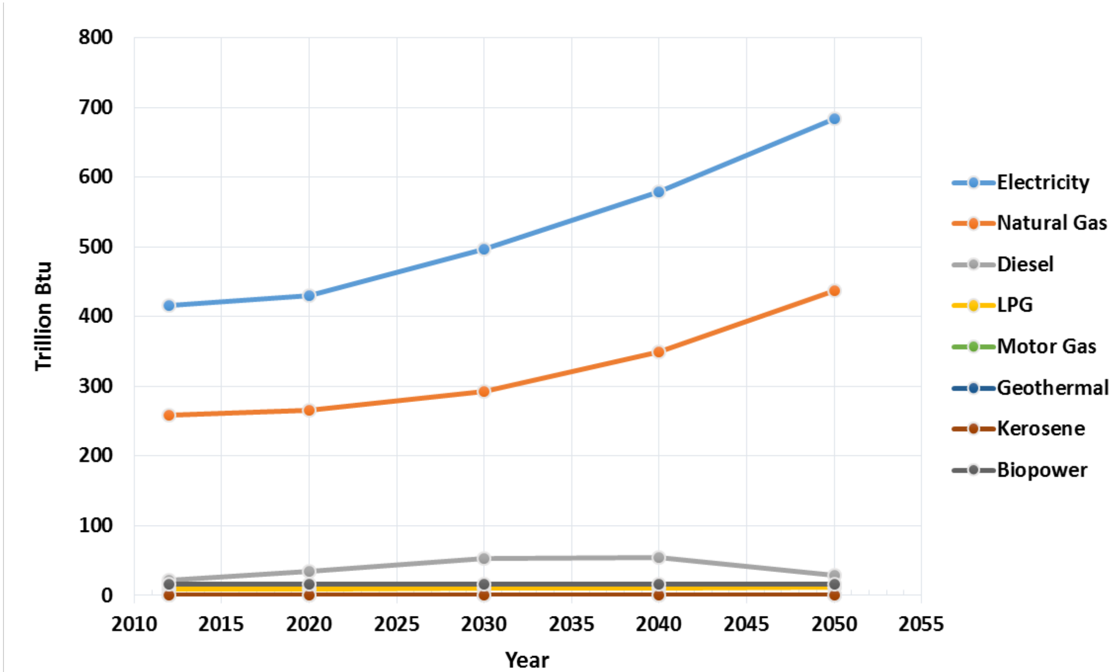


Figure 35 displays a huge increase in industrial use of other petroleum products from 2030 to 2050, which results from higher energy demand caused by economic growth as well as lower projected price of petroleum compared to electricity and natural gas.

Figure 35: California Industrial Energy Consumption Projections by Fuel

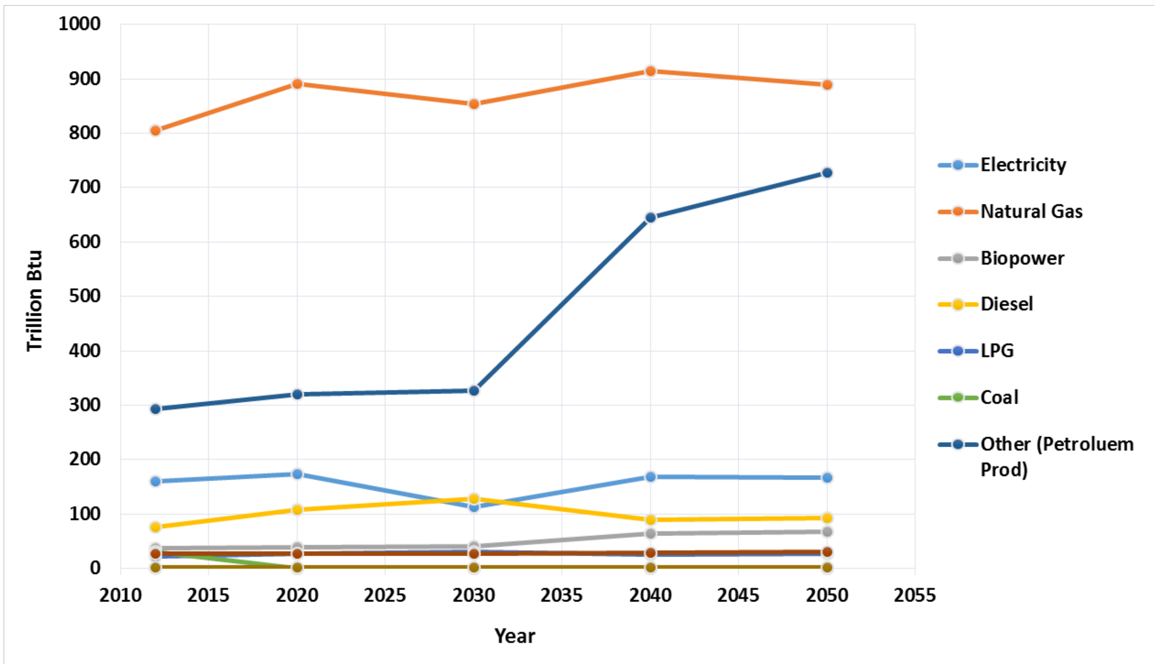
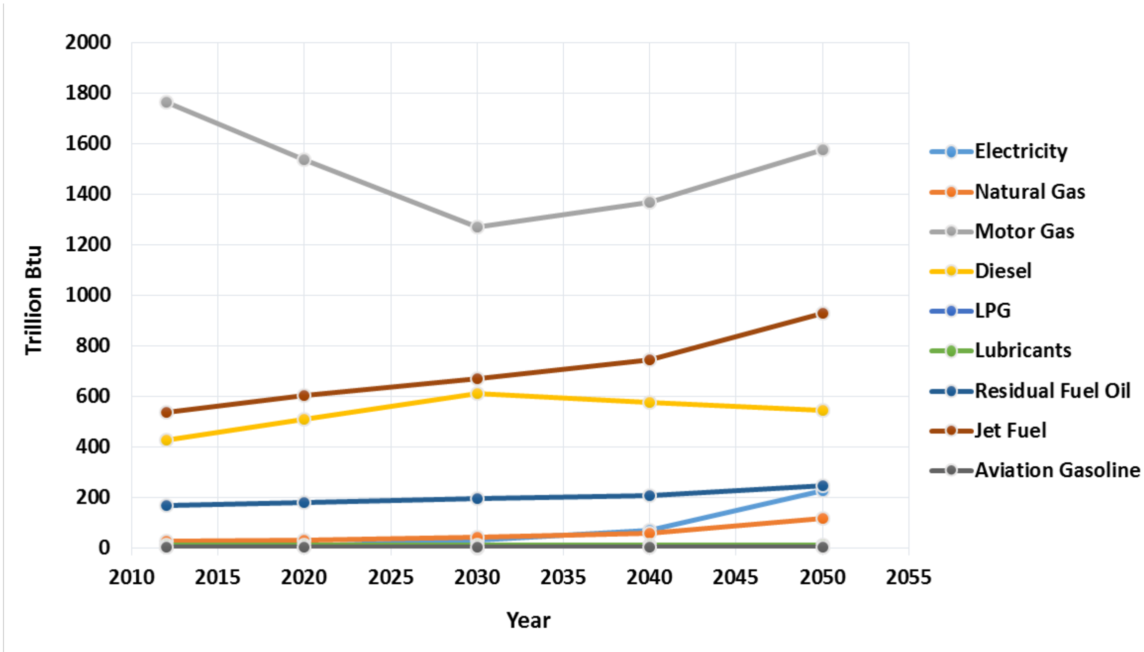


Figure 36 shows a significant reduction in transportation use of gasoline from 2012 to 2030, due to higher efficiency of advanced combustion engines, followed by a moderate increase from 2030 to 2050, which results from higher demand for transportation due to population growth.

Figure 36: California Transportation Energy Consumption Projections by Fuel



The BAU scenarios are developed under the assumption that no particular action is taken to push for further electrification and they follow a trend based on the projected prices of fuels as well as demand and supply laws. As seen from the results, the transportation and industrial sectors exhibit the lowest amounts of current electric penetration, indicating opportunity for new electrification. Electrifying more in these sectors will have a greater impact on air quality through reduced dependence on motor gas and diesel fuels. On the other hand, the commercial and residential sectors have the highest electricity and natural gas penetration by percentage. These values, in addition to renewable sources, can be increased overall as the demand increases. Particularly, the natural gas usage can be decreased and more electrification introduced.

3.1.1.2 MARKAL Projections by End-Use

To establish reasonable electrification scenarios, it is necessary to take the sector data a step further and determine the distribution of energy consumption by end-use. The EIA energy consumption surveys, which include national, regional, and some state level data, are used for conducting the projections. In order to project the possible end-use distribution, a procedure similar to that of fuel distribution is carried out. Figures 37-42 display the energy consumption projections of residential and commercial sectors by end-use.

Figure 37: California Residential Energy Consumption Projections by End-Use

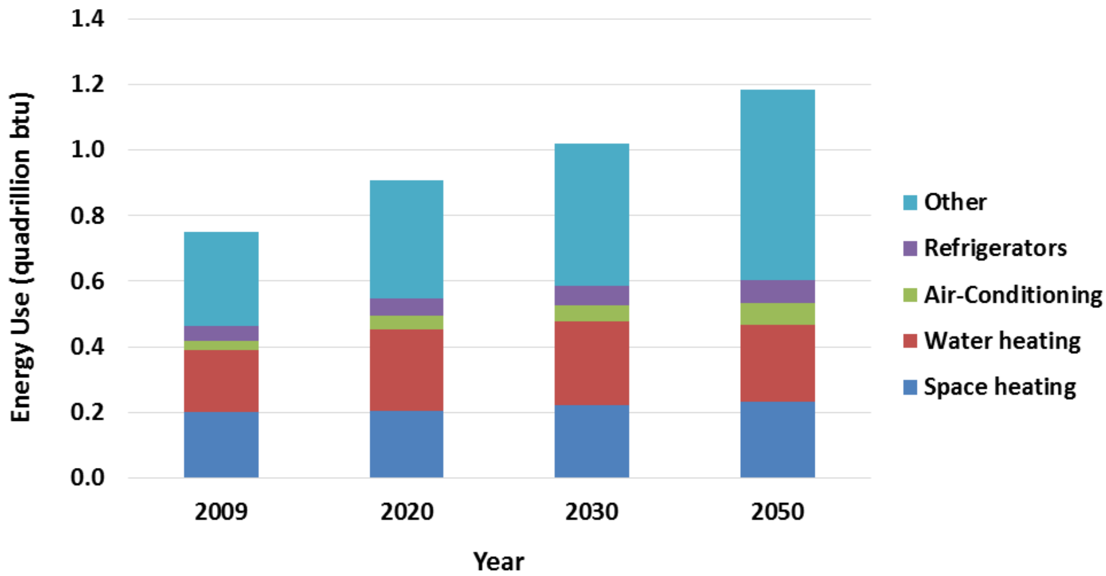


Figure 38: California Residential Electricity Consumption Projections by End-Use

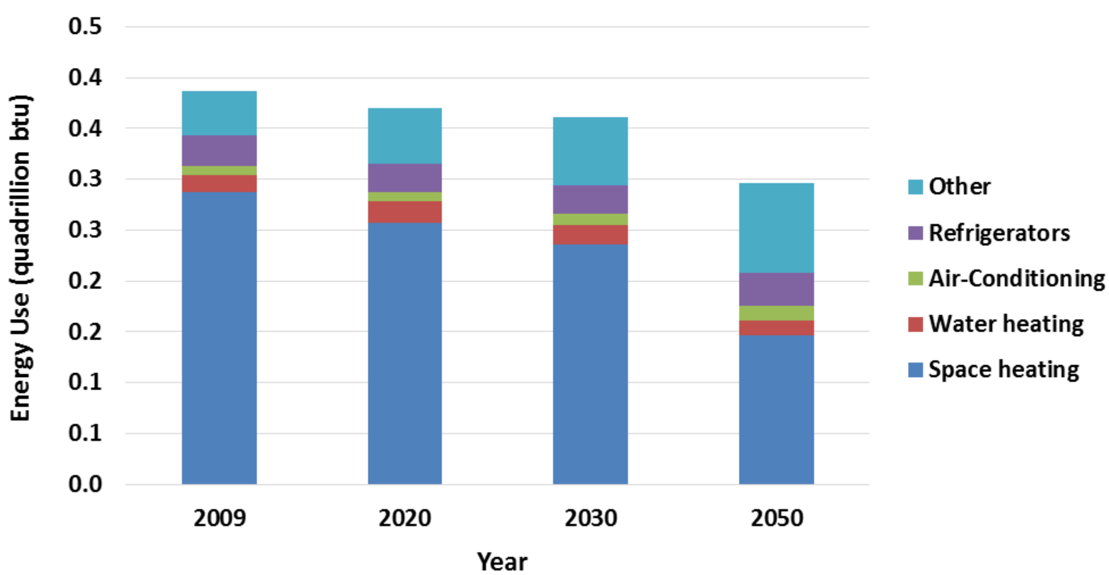


Figure 39: California Residential Natural Gas Consumption Projections by End-Use

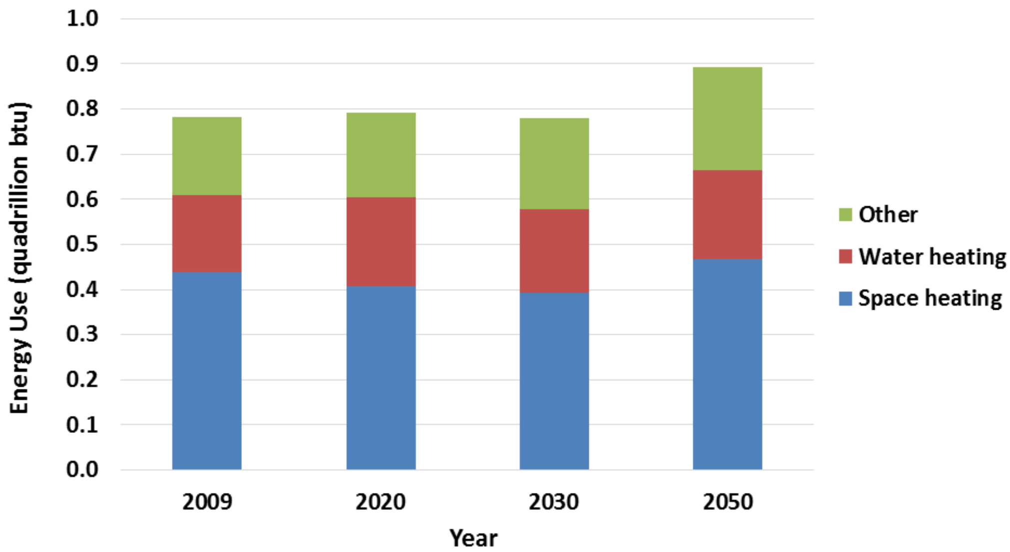


Figure 40: Pacific Region Commercial Energy Consumption Projections by End-Use

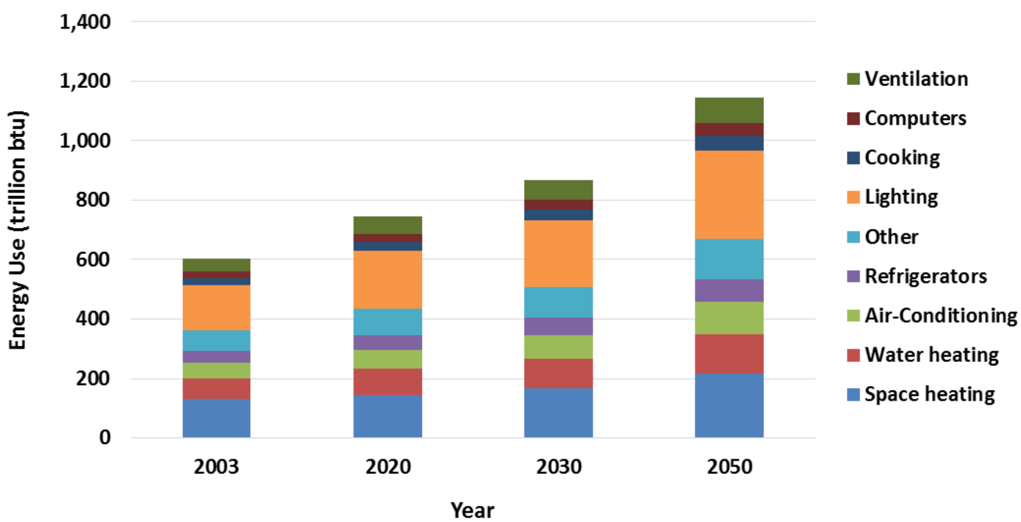


Figure 41: Pacific Region Commercial Electricity Consumption Projections by End-Use

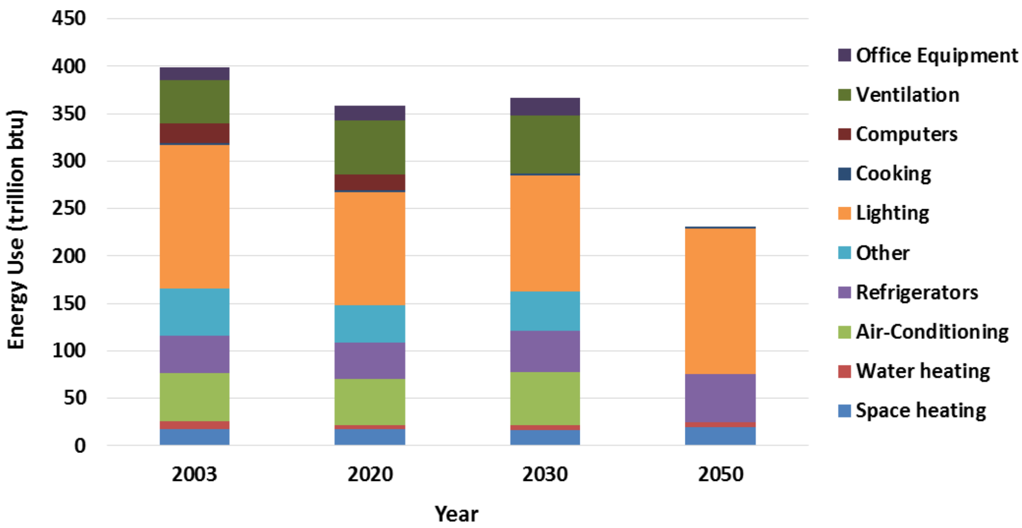
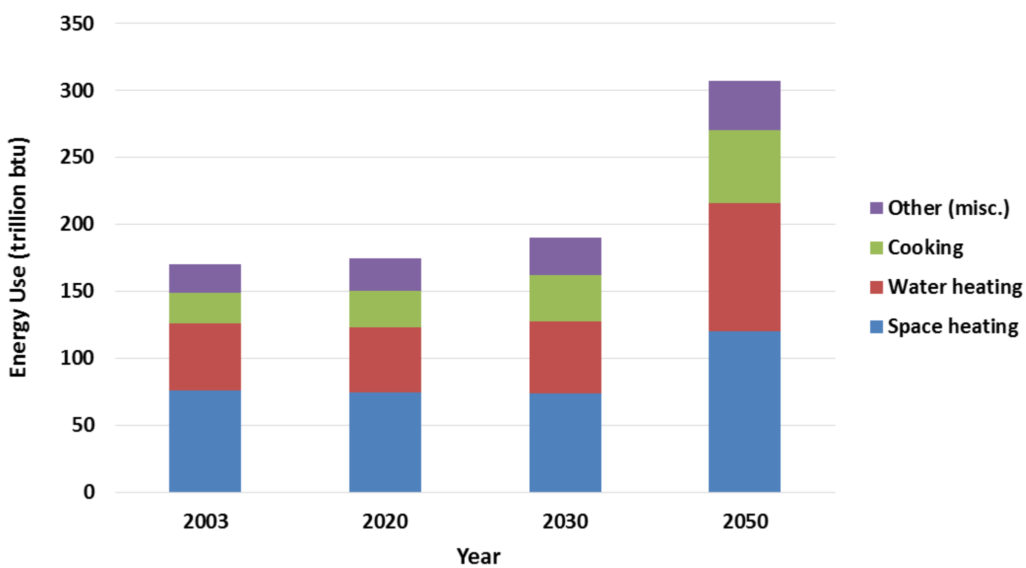


Figure 42: Pacific Region Commercial Sector Natural Gas Consumption Projections by End-Use



From this end-use data as well as the BAU projection data, we can conclude that there is a significant amount of potential for electrification in residential and commercial sector, especially in space heating, water heating, and cooking. In addition, we see even greater potential for electrification in the transportation sector for displacement of petroleum.

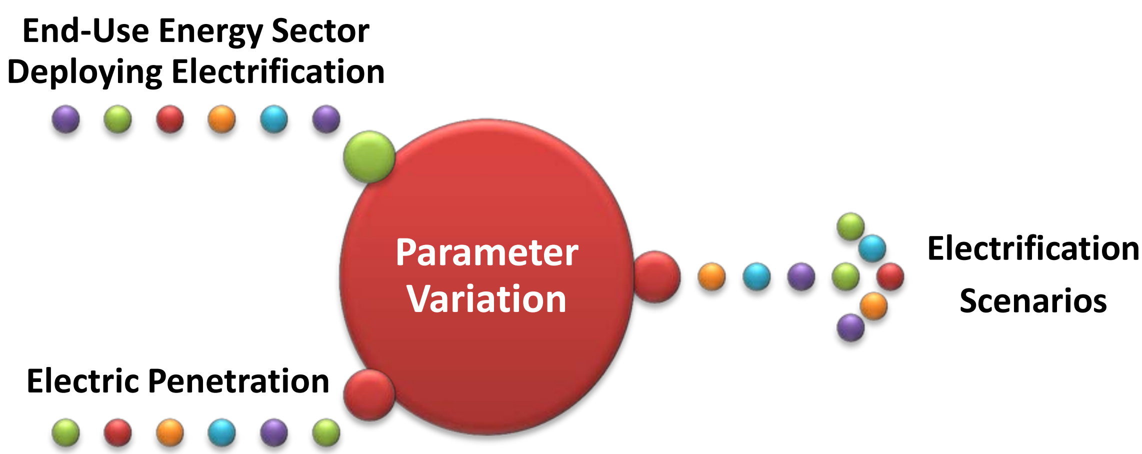
3.1.2 Development of Electrification Scenarios

Since there are no regulations on implementing electrification in state of California, the implementation scenarios are developed in a way that spans a wide spectrum of possibilities by considering different combinations of end-use energy sectors as well as varying electric penetrations. In addition, higher electric penetrations can be achieved in 2030 and 2050 due to mitigation of time, cost and technology barriers. Electrification scenarios are developed by considering change of electricity demand due to deployment of electrification in different end-use energy sectors. In other words, we are only concerned with changes in the California electricity demand profile when developing these scenarios.

3.1.2.1 Study Parameters

In this section, a set of key parameters are introduced which form the basis for development of electrification scenarios. The parameters considered are end-use energy sectors deploying electrification, electric penetration and smart grid technologies as shown in Figure 43. The scenarios are developed by varying these parameters and then emission assessments and air quality results are compared.

Figure 43: Electrification Scenario Development



<u>End-Use Energy Sectors Deploying Electrification</u>

As we discussed in section 3, each one of the end-use energy sectors has the potential of implementing electrification. Since many energy-consuming devices in residential and commercial buildings are already powered by electricity, the current electric penetration of these sectors is much higher than transportation and industrial sectors. Moreover, transportation sector is not anticipated to achieve high electric penetrations due to technology barriers that are not capable of meeting high power/energy density requirements of transportation modes such as aviation and marine transportation.

<u>Electric Penetration</u>

Electric penetration is essentially characterized by the percentage of end-use energy consumption that is supplied by electric power. This is the main parameter that needs to be specified when studying the air quality impacts of implementing electrification. Table 2 displays the current (2012) and projected (BAU) electric penetration of each end-use energy sector in 2020, 2030 and 2050.

Table 2: Current (2012) and Projected (BAU) Electric Penetration of End-Use Energy Sectors

Year	Residential	Commercial	Industrial	Transportation
2012	33.7%	57.5%	11%	0.1%
2020 BAU	34.9%	43.1%	11%	0.2%
2030 BAU	36.7%	43.8%	7.4%	1.1%
2050 BAU	40.2%	43.4%	7.5%	3.1%

3.1.3 Electrification Load Profile

Since there are no regulations on implementing electrification in state of California, the implementation scenarios are developed in a way that spans a wide spectrum of possibilities by considering different combinations of end-use energy sectors as well as varying electric penetrations. In addition, higher electric penetrations can be achieved in 2030 and 2050 due to mitigation of time, cost and technology barriers.

Contrary to renewable scenarios that were developed based on penetration of renewable energies in the electricity generation, electrification scenarios are developed by considering change of electricity demand due to deployment of electrification in different end-use energy sectors. In other words, we are only concerned with changes in the California electricity demand profile when developing these scenarios.

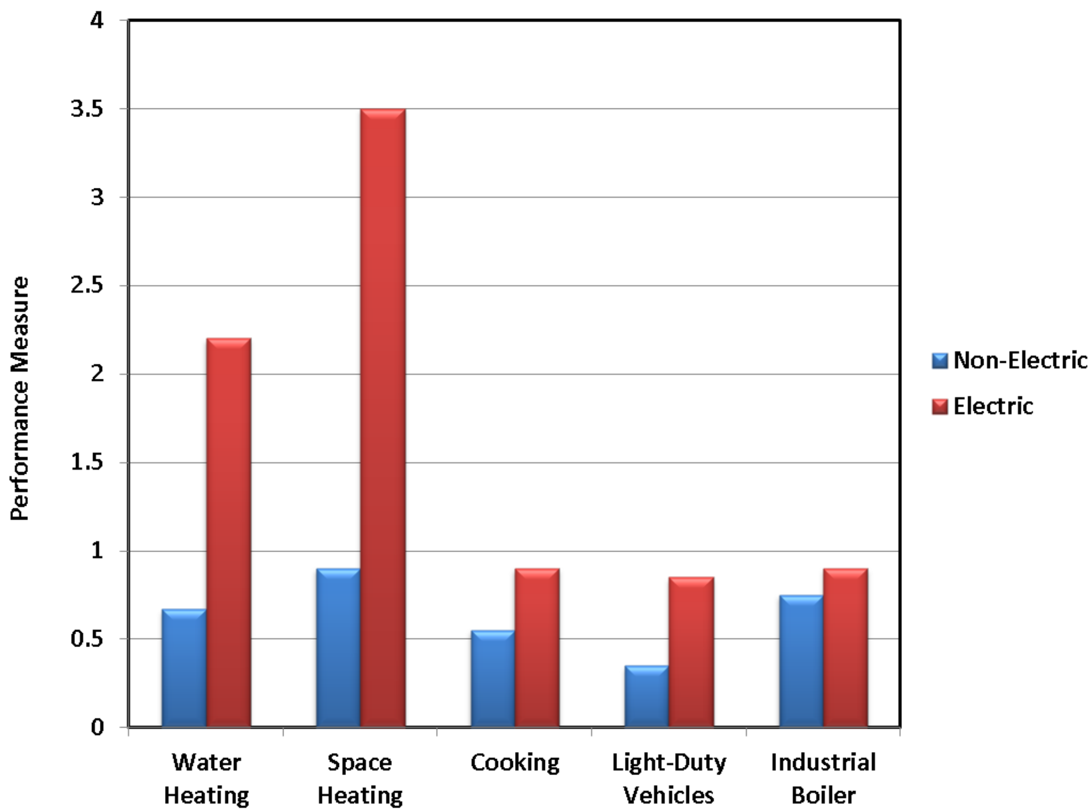
3.1.3.1 Efficiency Ratio

As we envision implementing electrification in California, the conventional non-electric devices – powered by fossil fuels, biomass, and biogas - have to be replaced by electric technologies. Although both technologies are designed to deliver the desired output, their performance characteristics can be significantly dissimilar meaning one technology can accomplish the same task with higher/lower efficiency. In each scenario, total electrification load is estimated by considering the efficiency ratio of non-electric vs electric technologies.

Figure 44 compares the performance characteristics of non-electric devices versus electric technologies. A natural gas-powered water heater can achieve efficiencies as high as 0.67, while electric heat pump water heaters have an average COP of 2.2 (American Council for an Energy-Efficient Economy, 2012). Although natural gas-powered space heaters are highly efficient (0.9), heat pump electric space heaters are far more efficient with an average COP of 3.5 (American Council for an Energy-Efficient Economy, 2012). The third energy-intensive residential/commercial end-use is cooking; a conventional gas cooker (stove or oven) can achieve efficiencies as high as 0.55, while the average efficiency of a modern induction electric cooker is 0.9.

Conventional ICE light-duty vehicles can achieve efficiencies as high as 0.35, while being outperformed by electric vehicles, which have an average tank-to-wheel efficiency of 0.85 (Yokoyama, 2009). Industrial gas-fired boilers best perform at efficiencies as high as 0.8, while industrial electric boilers have an average efficiency of 0.96 (Wilson, 2013).

Figure 44: Coefficient of Performance (COP) of Non-Electric vs Electric Technologies



3.1.3.2 Temporal Distribution

Electrification load profile is obtained by allocating the total electrification load using the temporal distribution of energy consumption in each end-use energy sector. Residential and commercial loads include only the energy used for space heating, water heating, and cooking activities. Residential load shape is estimated by modeling an average California residential building using eQuest (Hirsch, 1998-2014), while commercial load shape is obtained from temporal distribution of emissions associated with commercial activities in EPA emission inventory.

eQuest is a building energy simulation tool, which provides detailed analysis of current building technologies based on complicated energy simulation techniques. eQuest estimates hourly building energy consumption using historical weather data for the geographical location considered. The detailed specifications of building including hourly scheduling of residents, lighting, and thermostat settings are modified and used as the inputs of the model, while other factors such natural lighting, shading, envelope building mass, etc. are accurately simulated.

Figure 45 illustrates how the total energy consumption of end-use energy sectors is distributed throughout the year. Industrial sector is assumed to operate 24/7 with no disparity in operation throughout the year. Similarly, there is no monthly variation in energy consumption of transportation sector. However, residential and commercial energy consumptions are significantly varied throughout the year, with a peak on January, which is primarily due to high demand for space heating in cold seasons.

Figure 45: Normalized Monthly Distribution of End-Use Energy Consumption

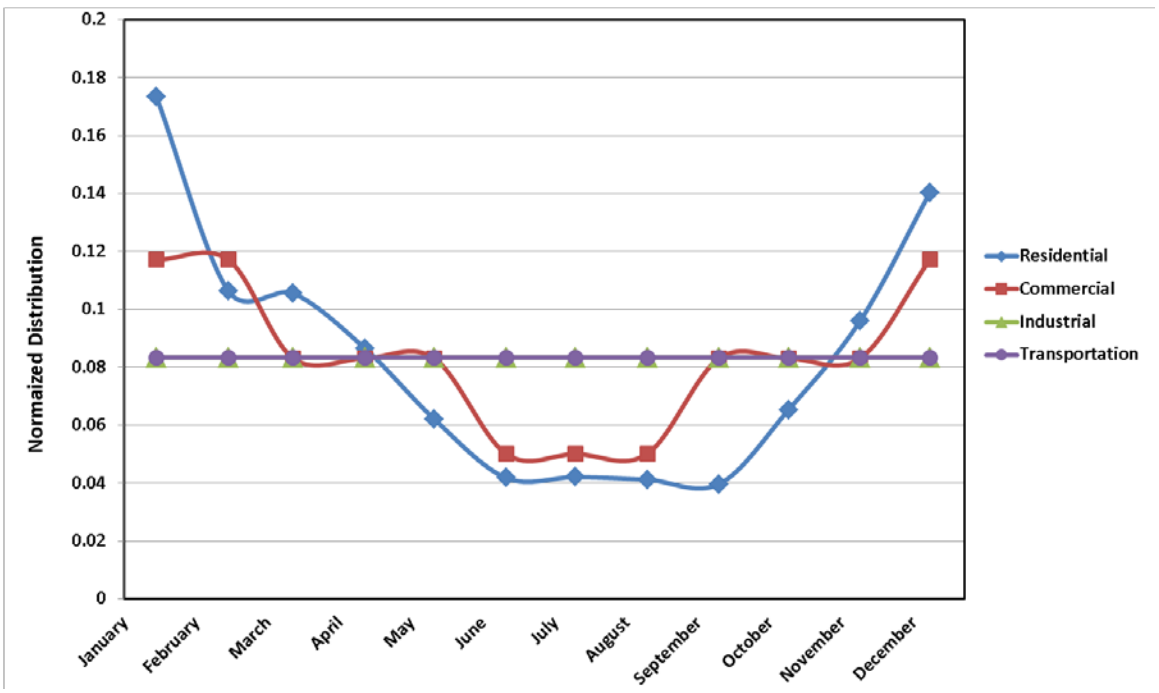


Figure 46 displays the variation of end-use energy consumptions throughout the week. Residential and commercial buildings use less energy during the weekends compared to weekdays, while transportation and industrial sectors are assumed to have no variation in energy use during the week.

Figure 46: Normalized Daily Distribution of End-Use Energy Consumption

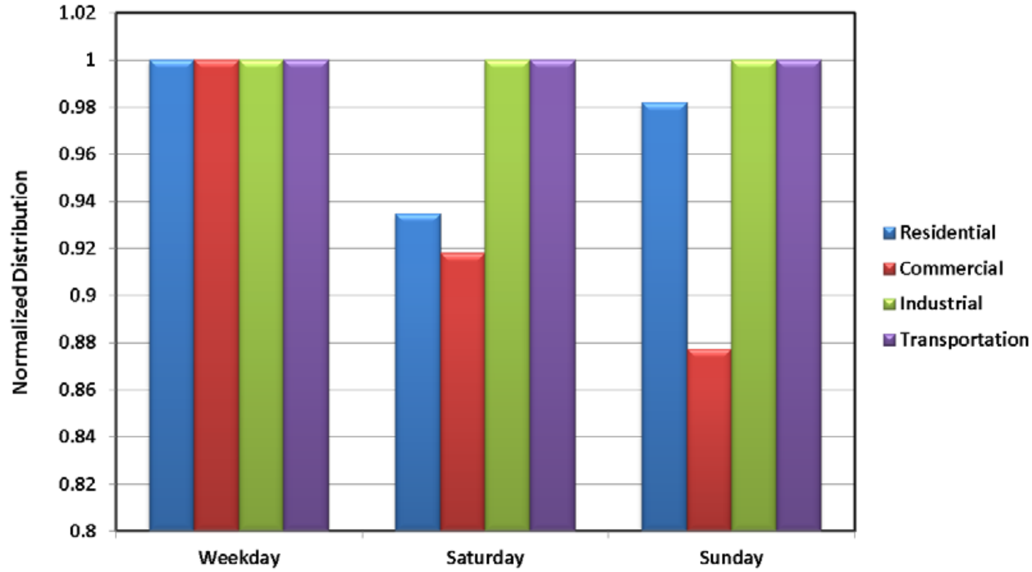


Figure 47: Normalized Hourly Distribution of End-Use Energy Consumption

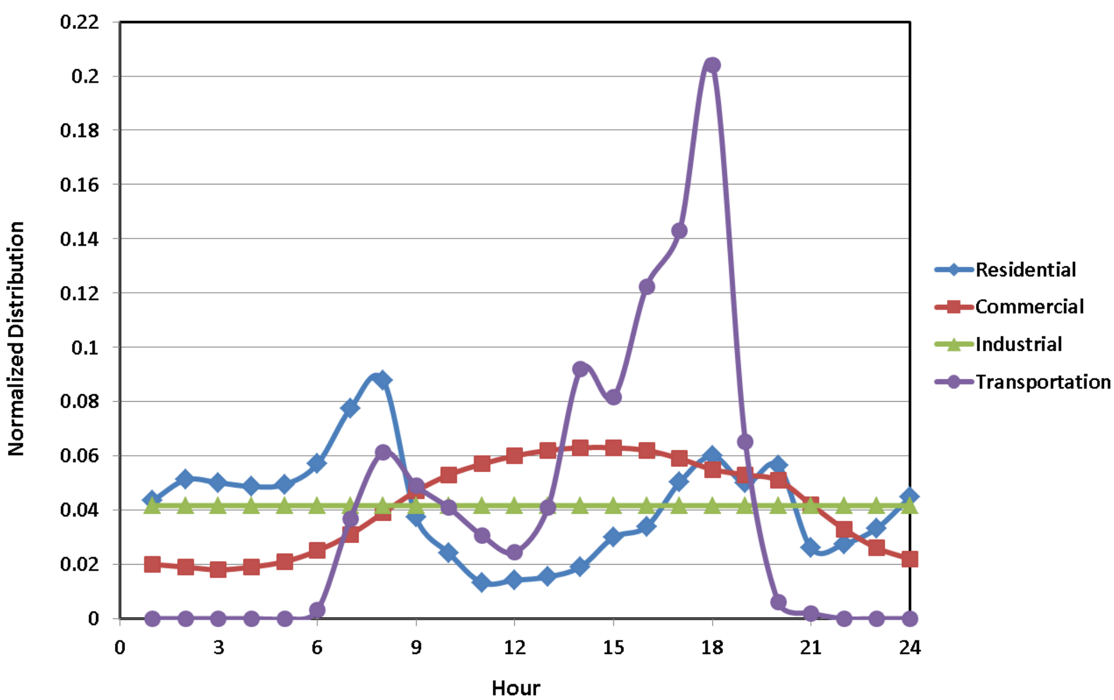


Figure 47 shows the hourly distribution of end-use energy consumption. Residential load peak occurs in the morning when there is a substantial demand for hot water, whereas commercial load increases in the morning, reaches the peak in the noon, and diminishes in the evening, which well follows the working time of commercial buildings. The transportation hourly load shape is based on the empirical data - average kWh consumed for immediate EV charging - gathered in ZEV-NET car-share program (Heling, et al., 2008). Since ZEV-NET employs immediate charging strategy, the majority of Electric vehicles are instantly charged after drivers return home from work, resulting in a huge spike in the evening. Therefore, there is no charging demand during night until early morning, when people arrive at work and start charging their electric vehicles.

3.2 Temporal Dispatch

3.2.1 Demand Load Profile

The 2020 electric load profiles are obtained from the CPUC renewable integration study (DOUGLAS, et al., 2009) by projecting the demand using Nexant, while accounting for energy efficiency measures, demand-side CHP, behind-the-meter PV, and non-event based demand response. Installed CHP and DR capacities are scaled to meet the incremental supply side CHP and DR targets. In CPUC study, 761 MW of incremental supply side CHP and 4,817 MW of incremental DR were assumed to be in operation by 2020. Non-event based DR was included in the load profiles rather than as supply side resource.

The 2030 and 2050 electric demand profiles are obtained by scaling the 2020 load profile based on the MARKAL projections of California total electricity demand. The load profile of each study year is then adjusted by adding the electrification load profile.

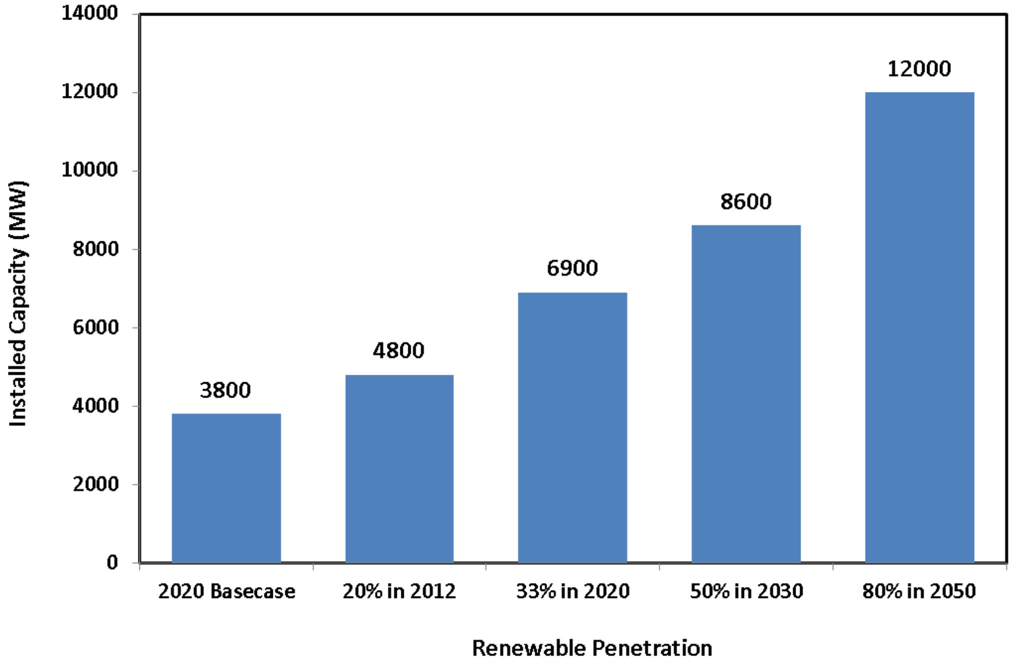
3.2.2 Complementary Technologies Dispatch

Increasing levels of renewable resources pose serious challenges to the gird operation due to unpredictable and intermittent nature of renewable energies. Power generation of renewable resources, such as wind and solar, can be highly dependent on weather conditions. Unexpected variation in weather conditions can cause significant perturbations in power generation. Therefore, installing higher levels of renewable power must be accompanied by deploying enhanced balancing strategies in order to sustain grid reliability.

The intermittent renewable power is conventionally balanced by load-following and peaking plants. However, increased intermittency due to higher penetrations of renewable resources is likely to result in higher levels of ramping and start-up emissions. This is mainly due lower efficiency and flawed emissions control strategies during part-load operation. Hence, the intermittencies due to renewable energies must be balanced by combining load-following and peaking power plants with alternative complementary technologies that include demand response, distributed generation, energy storage, and plug-in electric vehicles. The alternative complementary technologies are dispatched by HiGRID, which is an electric grid simulation tool developed at UCI (Eichman, et al., 2012).

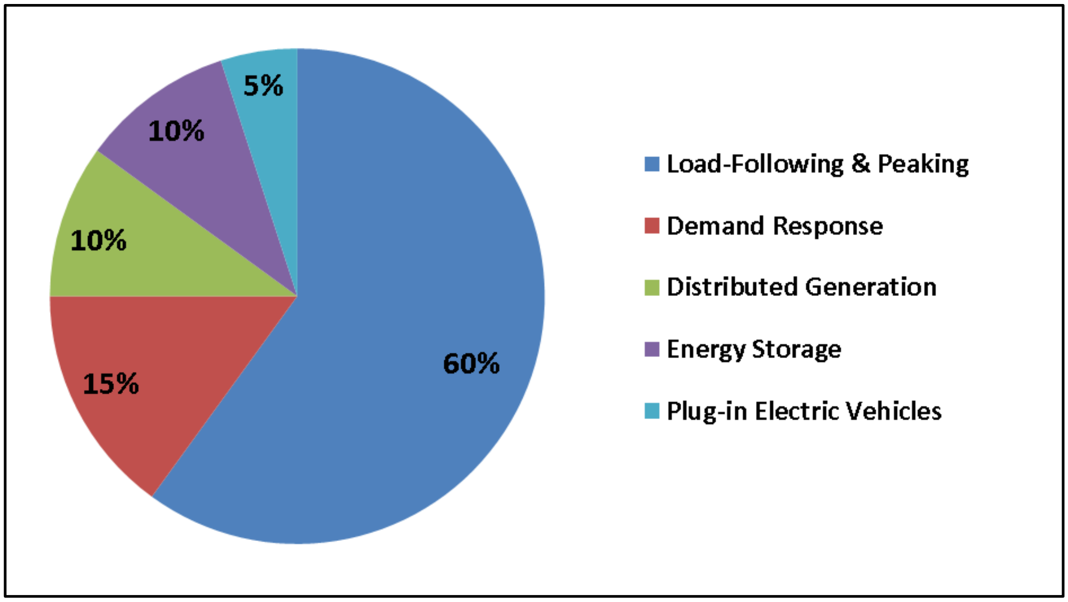
The required installed capacity of complementary technologies is determined based on the results from CAISO renewable integration study (California Independent System Operator, 2010). Figure 48 shows that 6900 MW, 8600 MW, and 12000 MW of complementary technologies are required to increase the renewable penetration to 33% in 2020, 50% in 2030, and 80% in 2050 respectively.

Figure 48: Required Complementary Technology Capacity



The complementary technologies used in this study comprise 60 percent load following and peaking natural gas fired power plants and 40 percent alternative complementary technologies. Figure 49 displays the detailed breakdown of complementary technology mix; Alternative complementary technologies consist of 37.5 percent demand response, 25 percent energy storage, 25 percent distributed generation, and 12.5 percent plug-in electric vehicles.

Figure 49: Complementary Technology Mix



After adjusting the original demand by adding the electrification load, the modified demand is then used as the input load profile for HiGRID model in order to determine the temporal dispatch profile of alternative complementary technologies as well as renewable resources. The alternative complementary technologies are dispatched in order of flexibility. Demand response is the first resource to integrate, which can complement the grid through load shifting, peak smoothing, and reserve margin. Demand response is enabled using various technologies including smart meters, smart appliances, building pre-cooling, etc.

Plug-in hybrid electric vehicle is the second technology to dispatch, that can balance the grid by storing excess renewable power, as the case where huge amount of wind energy is available during the night when the electric demand is low.

Energy storage can support the grid through load balancing and peak shifting. Energy storage technologies store excess energy for later use, but with some energy loss, and release it to the grid when needed. In order to balance the intermittencies due to renewable power, storage technologies with higher energy capacities and longer discharge times are required. Compressed air energy storage, pumped hydro, and flow batteries are storage technologies considered in this study.

Distributed generation can complement the grid by generating electric power using micro turbine generators and fuel cells. Distributed generation can achieve superior efficiencies compared to centralized generation, since there are no transmission/distribution losses, and the waste heat can be recovered and used on site. Moreover, DG emissions are significantly lower since fuel cells have low-to-zero emissions.

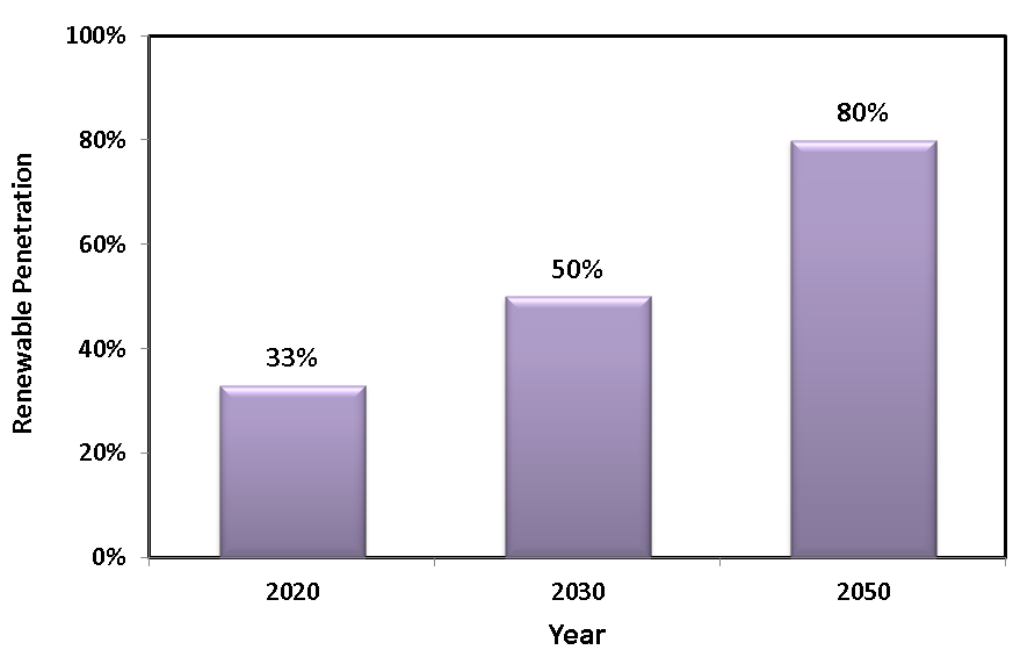
3.2.3 Renewable Dispatch

In 2002, the California Renewable Portfolio Standard was initiated, which initially set a goal of 20% renewable energy penetration by 2017, which was later accelerated to achieve by 2010. In 2011, the California Renewable Portfolio Standard was expanded and an additional goal of 33% renewable energy penetration by 2020 was regulated.

Alongside renewable penetration targets, GHG emission reduction goals have been emerging since higher levels of renewable resources is anticipated to significantly lower GHG emissions in the state. In 2006, the GHG emission reduction target was set to achieve 1990 levels by 2020 and 80% below 1990 levels by 2050 by Assembly Bill 32 (AB32).

Since there are no regulations on renewable energy goals in 2030 and 2050, it is assumed that renewable penetration increases to 50% by 2030 and 80% by 2050 (Figure 50). The amount of required renewable generation is directly proportional to the load since renewable targets are characterized in percentage rather than total energy.

Figure 50: Renewable Energy Penetration Targets

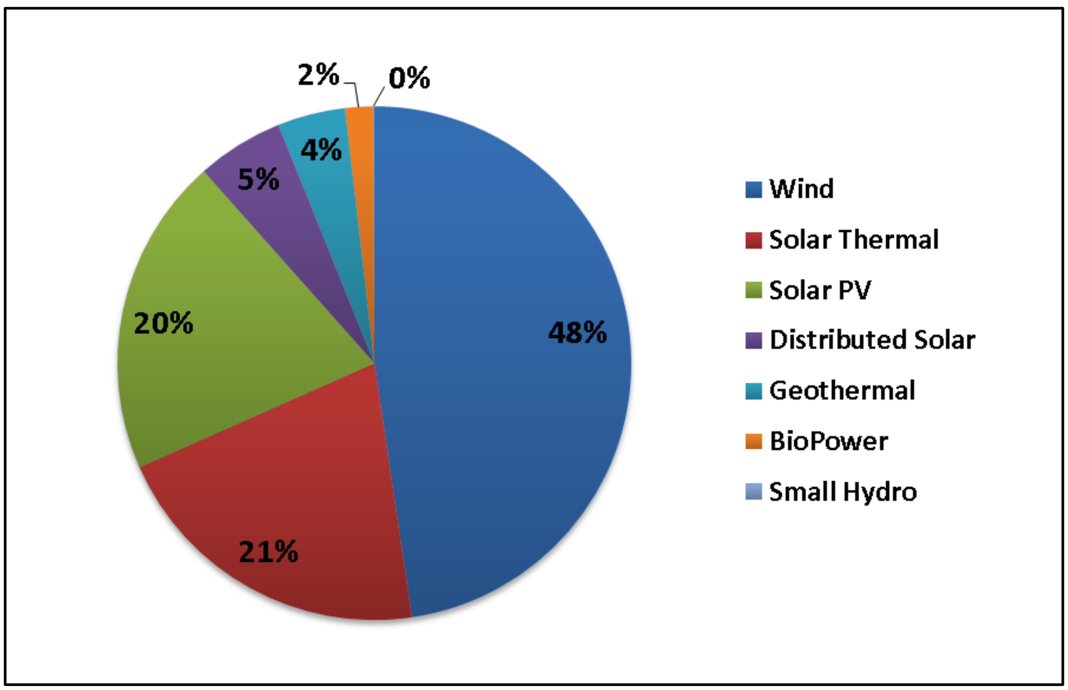


In this study, the renewable energy mix is determined based off the scenarios developed in CAISO/CPUC renewable integration study (Table 3). It was found that the trajectory scenario would result in lower emissions and enhanced air quality (Tan & Brouwer, 2013). Therefore, the renewable energy mix in the trajectory scenario, displayed in Figure 51, is used for achieving the renewable penetration goals. The temporal load profile of renewable energies is determined by HiGRID, based on the incremental capacity of renewable energies, availability of resources and load balancing constraints.

Table 3: CAISO/CPUC 33% Renewable Scenarios

Scenario	Region	Incremental Capacity (MW) Biomass/ Biogas	Geothermal	Small Hydro	Solar PV	Distributed Solar	Solar Thermal	Wind	Total
Trajectory	CREZ-North CA	3	0	0	900	0	0	1,205	**2,108**
	CREZ-South CA	30	667	0	2,344	0	3,069	3,830	**9,940**
	Out-of-State	34	154	16	340	0	400	4,149	**5,093**
	Non-CREZ	271	0	0	283	1,052	520	0	**2,126**
	Scenario Total	338	821	16	3,867	1,052	3,989	9,184	**19,266**
Environmentally Constrained	CREZ-North CA	25	0	0	1,700	0	0	375	**2,100**
	CREZ-South CA	158	240	0	565	0	922	4,051	**5,935**
	Out-of-State	222	270	132	340	0	400	1,454	**2,818**
	Non-CREZ	399	0	0	50	9,077	150	0	**9,676**
	Scenario Total	804	510	132	2,655	9,077	1,472	5,880	**20,530**
Cost Constrained	CREZ-North CA	0	22	0	900	0	0	378	**1,300**
	CREZ-South CA	60	776	0	599	0	1,129	4,569	**7,133**
	Out-of-State	202	202	14	340	0	400	5,639	**6,798**
	Non-CREZ	399	0	0	50	1,052	150	611	**2,263**
	Scenario Total	661	1,000	14	1,889	1,052	1,679	11,198	**17,493**
Time Constrained	CREZ-North CA	22	0	0	900	0	0	78	**1,000**
	CREZ-South CA	94	0	0	1,593	0	934	4,206	**6,826**
	Out-of-State	177	158	223	340	0	400	7,276	**8,574**
	Non-CREZ	268	0	0	50	2,322	150	611	**3,402**
	Scenario Total	560	158	223	2,883	2,322	1,484	12,171	**19,802**

Figure 51: Trajectory Renewable Energy Mix



3.2.4 Generators Dispatch

Once temporal dispatch profiles of renewable resources and alternative complementary technologies are determined by HiGrid, these profiles are subtracted from the demand profile and the adjusted demand profile is then used as the input load profile for PLEXOS model in order to dispatch the power plants. PLEXOS is a grid simulation tool that dispatch generators based on economic standards (Drayton, 2014). The entire power grid system is divided into nodes and transmission lines. Loads for each node are determined from the input load profile and generators are then dispatched, while considering transmission constraints throughout the WECC region.

3.3 Emissions Assessment

Electric power sector emits various types of emissions including criteria pollutants, greenhouse gas emissions, and hazardous air pollutant emissions. In this study, we only consider criteria pollutants and greenhouse gas emissions. Criteria pollutant emissions cause air quality issues whereas greenhouse gas emissions contribute to global warming.

3.3.1 Criteria Pollutant Emissions

Primary criteria pollutants generated directly by combustion include particulate matter (PM), SO_2, CO, and lead. Ozone (O_3) and Nitrogen Dioxide (NO_2) are known as secondary criteria pollutant emissions, since they are created in the atmosphere due to chemical reaction of primary criteria pollutants.

The criteria pollutant emissions of each scenario is analyzed and processed as the input file for simulation of atmospheric chemistry. The criteria pollutant emissions are required to be spatially and temporally resolved for introducing to the air quality model. Baseline criteria pollutants such as nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter (PM), carbon monoxide (CO), and non-metallic organic compounds (NMOC) are estimated based on the power generation characteristics.

3.3.1.1 Power Plants Emissions

<u>Steady State Emissions</u>

The steady-state emissions factors of power plants are obtained from eGRID, which is an environmental characteristics database (Environmental Protection Agency, 2012). EPA generic emission factors are used for generators that are not included in eGRID (Table 4). The emissions factors are in pounds per Million Btu; therefore, they must be used along with the generator heat rates, obtained from PLEXOS, in order to determine the steady state emission factors in pounds per MWh.

Table 4: EPA Generic Emissions Factors (lb/MMBtu)

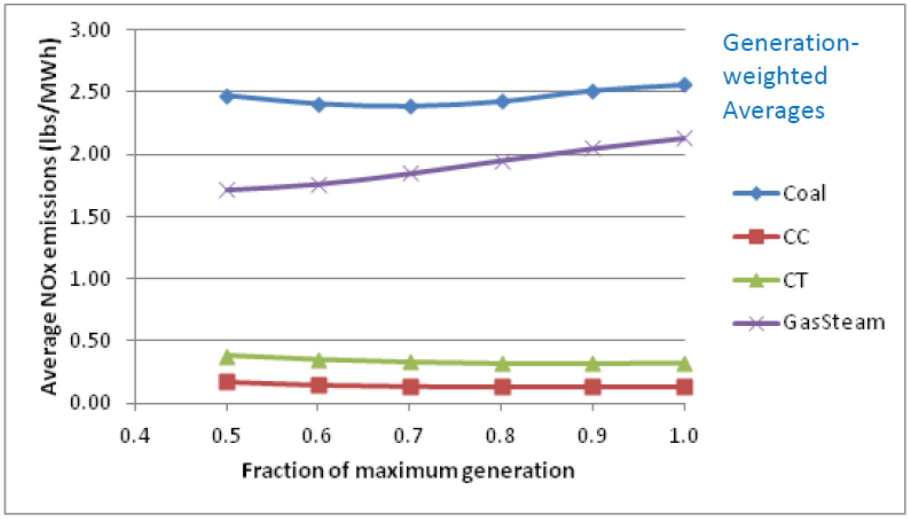
Fuel		NO_x	SO_2	CO	PM_{10}	NMTOC
NG GT	NG GT	0.0128	0.00338	0.0295	0.00663	0.00206
	NG CC	0.0128	0.00338	0.0295	0.00663	0.00206
NG ST	NG ST	0.07451	0.000588	0.096078	0.007451	0.008529
NG IC Low Load < 90		0.227	0.000588	0.351	0.0095	0.128
NG IC High Load > 90	NG IC	0.221	0.000588	0.372	0.0095	0.128
DGas	Biogas	0.007073	0.00653	0.017	0.012	0.00582
WDS	Bio	0.22	0.025	0.06	0.035	0.018
ST DFO	Oil	0.003571	0.020286	0.035714	0.000607	0.005429
	PC	0.003571	0.020286	0.035714	0.000607	0.005429
Coal Bit	Coal	0.080769	0.021154	0.192308	0.004062	0.001923

Source: (Tan & Brouwer, 2013)

Dynamic Emissions

Part-load emission factors are estimated based on the emission trends determined in the Western Wind and Solar Integration Study (National Renewable Energy Laboratory, 2010). As Figure 52 illustrates, the part-load emission factors are determined by computing the percentage increases of NOx emissions at 50% capacities.

Figure 52: Part-load NOx Emissions



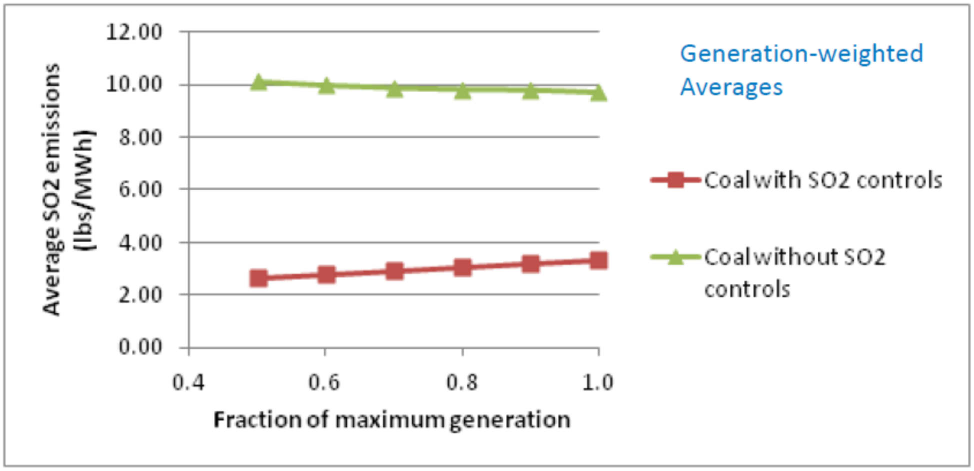
Percentage increase in NO_x/MWh at 50% of capacity.

Coal	Gas CC	Gas CT	Gas steam
-3%	29%	16%	-19%

Source: (National Renewable Energy Laboratory, 2010)

Figure 53 shows part-load SO_2 emissions, which are determined based on the average SO_2 emission trends. Startup and ramping emission factors are also obtained from Western Wind and Solar Integration Study (Table 5).

Figure 53: Part-load SO_2 Emissions



Percentage increase in SO_2 emission/MWh at 50% of capacity.

Coal (controlled)	Coal (uncontrolled)
-20%	4%

Source: (National Renewable Energy Laboratory, 2010)

Table 5: Startup and Ramping Emissions

Startups

	CO_2	NO_x	SO_2
Coal	1.2	1.0	0.8
Gas CC	0.3	6.1	n/a
Gas CT	0.4	1.8	n/a
Gas steam	0.9	0.0	n/a

Ramping

	CO_2	NO_x	SO_2
Coal	0.03	0.08	0.07
Gas CC	0.01	0.08	n/a
Gas CT	0.01	0.01	n/a
Gas steam	0.01	0.08	n/a

Startup and ramping emission penalty listed in hours of equivalent full-load operation. Coal units emit less NO_x during startup relative to full-load operation. Ramping leads to far less emissions compared to startups, but occurs more often.

Source: (National Renewable Energy Laboratory, 2010)

Table 6 summarizes part-load and dynamic emission factors. Part-load NOx emissions are estimated by applying the emission factor, which is obtained by interpolating 50% part-load and full-load NOx emission factors, to the power plant generation profile. If power generation is below half capacity, 50% part-load emission factor is used for emission estimations. Startup emissions are considered when power generation changes from zero to a non-zero value, while ramping emissions are applied when power generation increases at least by 30%. Start-up and ramping emissions are determined by multiplying their penalties to the full-load steady-state emission.

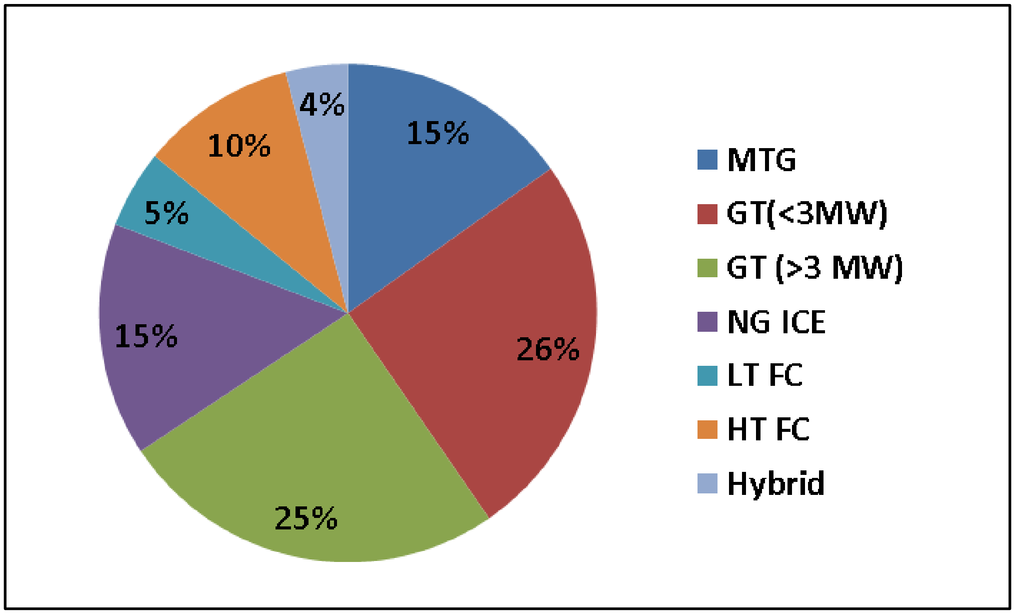
Table 6: Dynamic Emissions

Generator Type	NOx Start-Up Penalty	NOx Ramping Penalty	50% Part-Load NOx Emission Factor	Full-Load NOx Emission Factor
NG GT	1.8	0.01	0.16	0.1344
NG CC	6.1	0.08	0.29	0.4571
NG ST	0.0	0.08	-0.19	0.0745
NG IC	0.0	0.08	0.03	0.2210
Coal	1.0	0.08	-0.03	0.0808

3.3.1.2 Distributed Generation Emissions

DG emissions are determined based on its technology mix, which is determined based on the scenarios developed by Medrano et al (Medrano & Brouwer, 2008). However, Solar PV is removed from the technology mix since it is not capable of load balancing. The criteria pollutant emissions of distributed generation are estimated by averaging the emissions factors of all DG technologies based on the technology mix, which is displayed in Figure 54; Fifteen percent of DG is met by micro turbine generators, while gas turbines make up nearly half of total DG power. Internal combustion engines and fuel cells are the next largest contributors with each generating 15% of total DG power.

Figure 54: Distributed Generation Technology Mix



Source: (Medrano & Brouwer, 2008)

Table 7: Criteria Pollutant Emissions of Distributed Generation Technologies

DG Technology	Efficiency (Based on HHV)	CO (lb/MWh)	VOC (lb/MWh)	NO_x (lb/MWh)	SO_x (lb/MWh)	PM (lb/MWh)
MTG	0.27	0.10	0.02	0.07	0.01	0.08
GT(<3MW)	0.24	0.31	0.04	0.46	0.01	0.09
GT (>3 MW)	0.36	0.21	0.02	0.13	0.01	0.06
NG ICE	0.32	1.77	0.44	0.44	0.01	0.07
LT FC	0.36	0.10	0.02	0.07	0.01	0.06
HT FC	0.48	0.10	0.02	0.07	0.01	0.05
Hybrid	0.70	0.10	0.02	0.07	0.00	0.03
DR Average	0.33	0.43	0.09	0.24	0.01	0.07

Source: (Medrano & Brouwer, 2008)

Table 8 and Table 9 show the average full-load and dynamic DG emission factors in pounds per MWh (lb/MWh) respectively. Part-load emissions are applied to the DG generation profiles by interpolating the 50% part-load and the full-load NO_x emission factors. If DG generation is below half capacity, the 50% part-load emissions factor is used. Startup emissions are considered when DG power generation changes from zero to a non-zero value, while ramping emissions are applied when power generation increases at least by 30%.

Table 8: Average Full-Load DG Emissions

Full Load Emissions (lb/MWh)				
NO_x	SO_x	CO	PM_{10}	NMTOC
0.2373	0.0097	0.4295	0.0692	0.0878

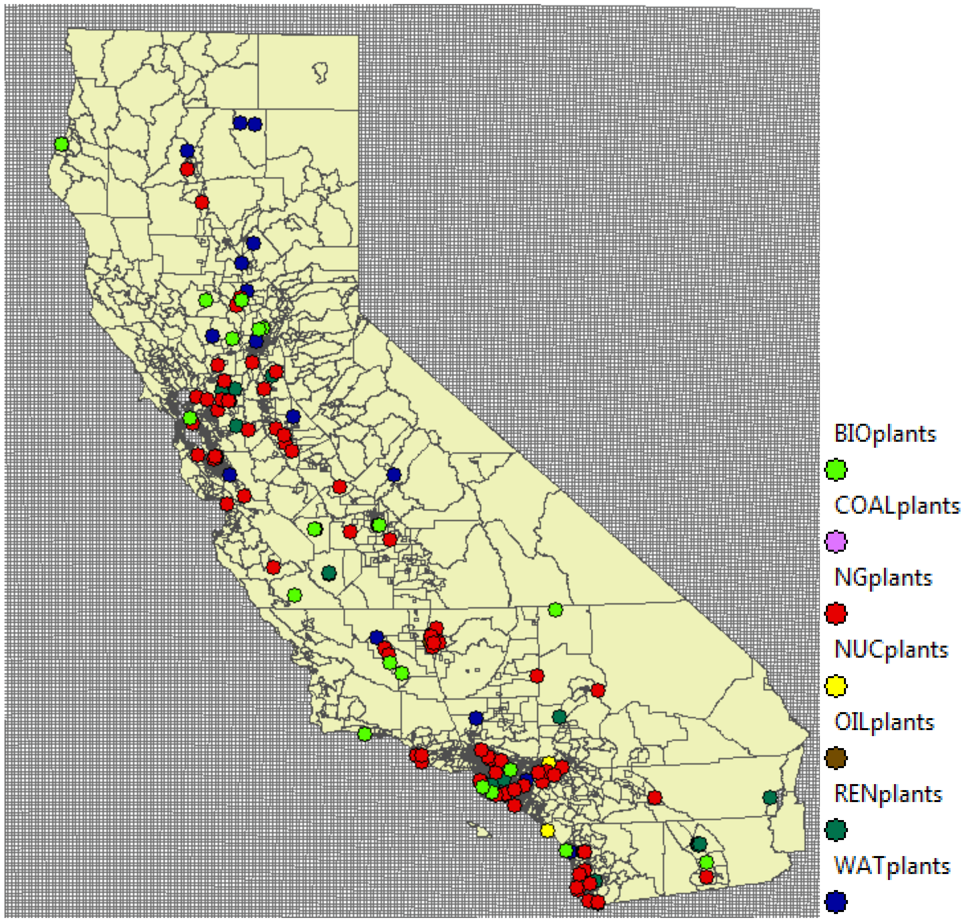
Table 9: Average Dynamic DG Emissions

Part-Load Emissions	**50% Part-Load NOx**	**Full-Load NOx**
Percentage Increase	16%	0%
Part Load Emissions (lb/MWh)	0.4982	0.2373
Dynamic Emissions	**Start-up NOx Penalty**	**Ramping NOx Penalty**
Hours of Equivalent Full-Load Emissions	1.8	0.01
Emissions per MWh of Full-Load Power (lb/MWh of Full Load)	0.42714	0.00237

3.3.2 Spatial Locations

The criteria pollutant emissions must be spatially resolved for presenting to air quality modeling. The locations of majority of existing power plants are available through eGRID (Environmental Protection Agency, 2012). Spatial Coordinates of other power plants were determined through various online searches (Tan & Brouwer, 2013). Figure 55 shows the location of existing power plants, developed by eGRID.

Figure 55: eGRID power plant locations



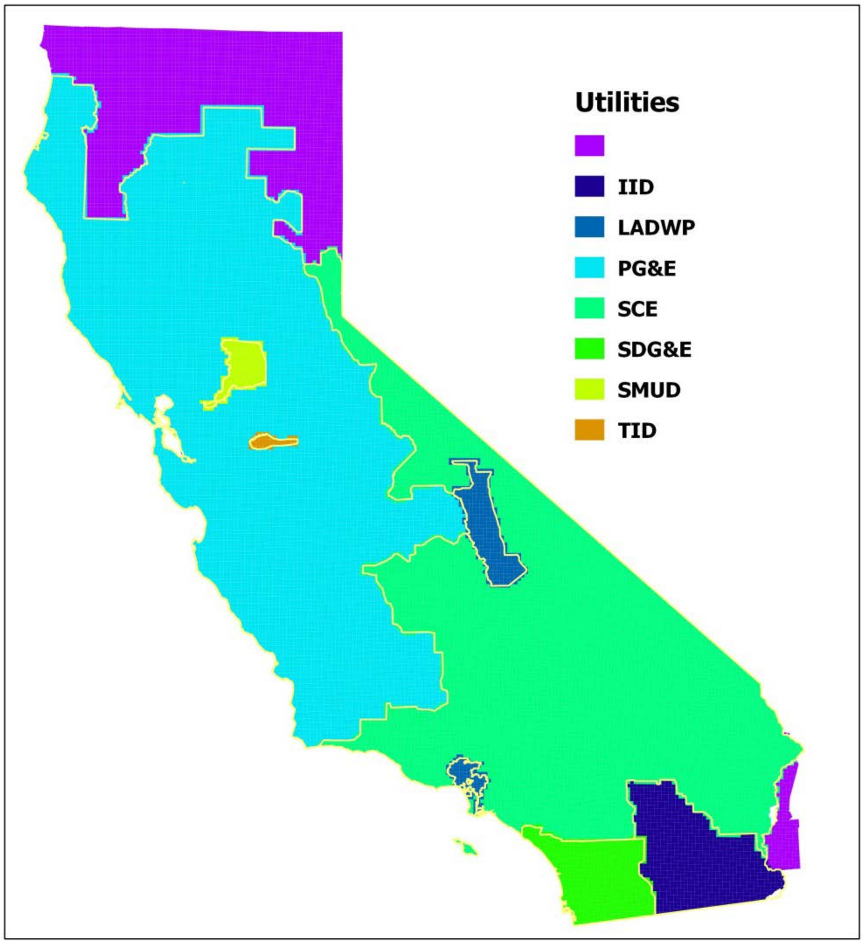
Source: (Environmental Protection Agency, 2012)

3.3.2.3 Distributed Generation Locations

ArcGIS land use data is used to determine the location of future power plants and distributed generation (Medrano & Brouwer, 2008). Criteria pollutant emissions from distributed generation are spatially distributed based on land use data (Figure 56). It is assumed that DG is mainly associated with industrial and commercial land use. Land use data, utility shape files, and grid mesh are integrated to find the fraction of total DG emissions in each 4 by 4 kilometer node.

The DG generation profiles are characterized by utility. Therefore, it is crucial to determine the utility that encompasses each node. Utility boundaries are used to develop their GIS shape files in graphics interchange format (Tan & Brouwer, 2013).

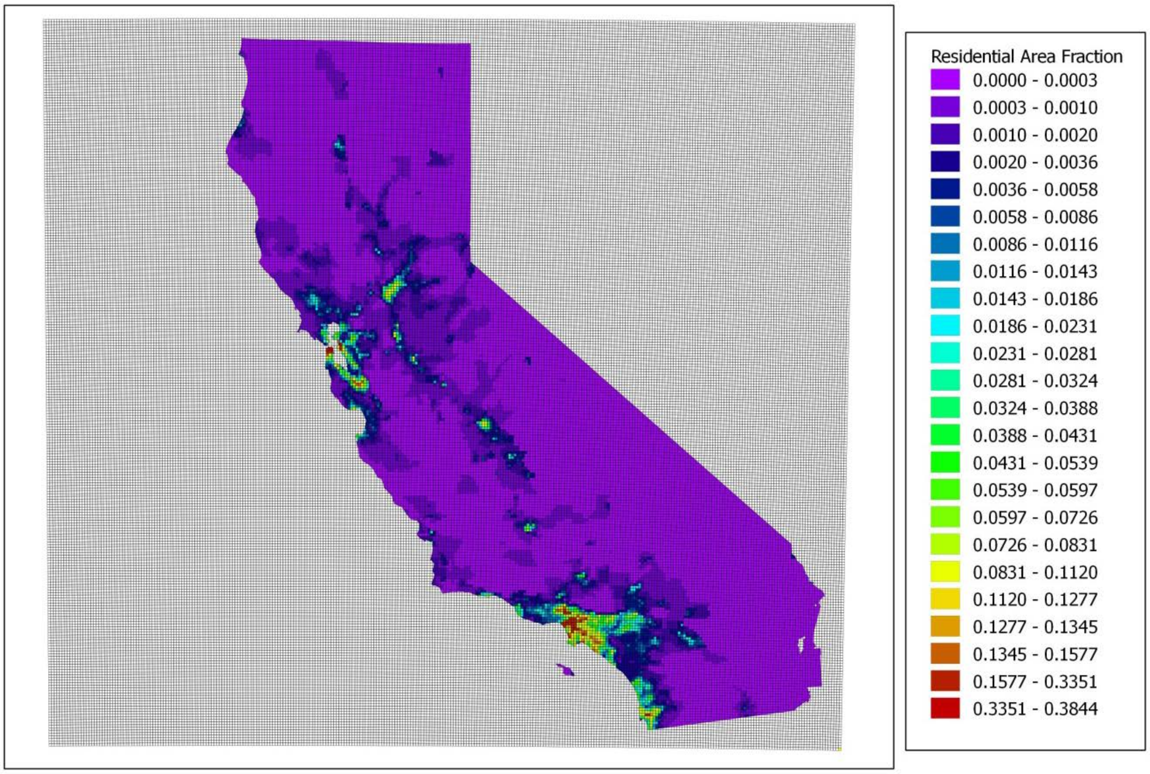
Figure 56: Integration of utilities, grid mesh, and land use data



Source: (Tan & Brouwer, 2013)

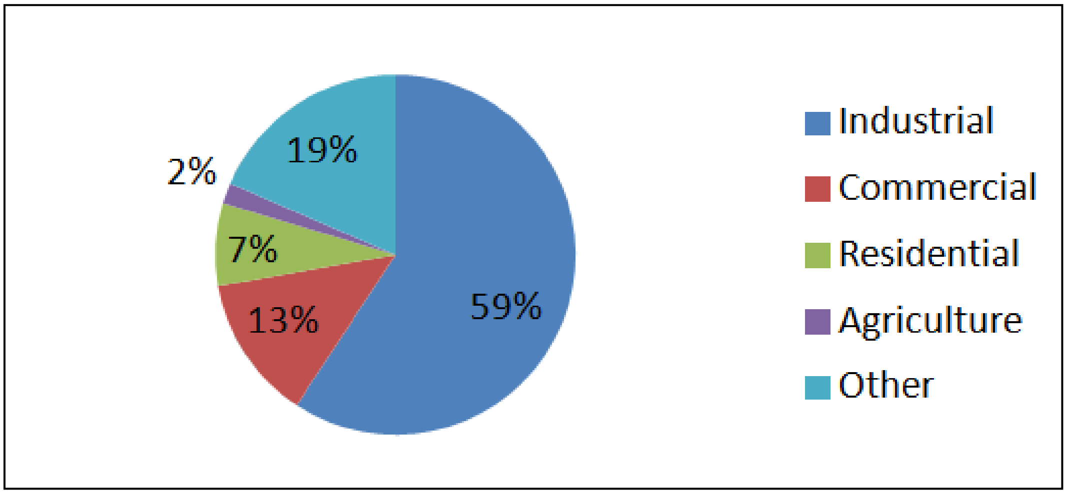
The distributed generation of each utility is weighted by land-use. Figure 57 shows an example of residential land use data. Although DG can be used for a wide variety of applications, it is expected correlate directly with Industrial applications. Hence, DG emissions are spatially resolved using weighted land-use data. Figure 58 illustrates the statewide average weights of each type of land-use.

Figure 57: Residential Land use in a 4 by 4 Km resolution



Source: (Tan & Brouwer, 2013)

Figure 58: DG Breakdown by Weighted Land-Use Data



Source: (Tan & Brouwer, 2013)

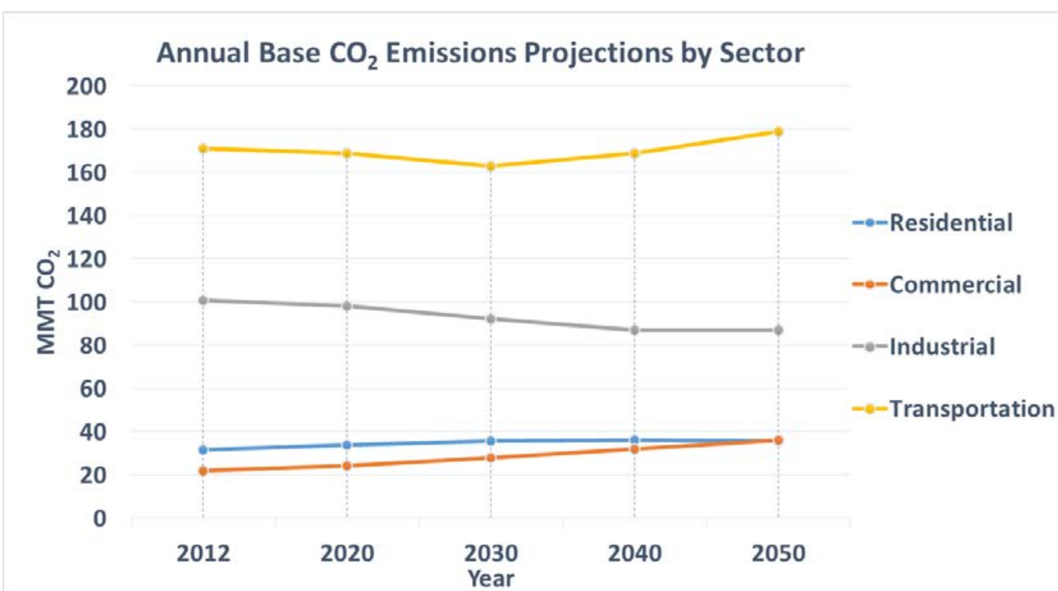
3.3.3 Greenhouse Gas Emissions

Estimation of impacts on GHG emissions in electrification scenarios involved methodologies for both power sector emissions and non-power sector emissions. Emissions from electricity generation was obtained directly as an output from the modeling framework described previously and was added directly to scenario totals. Non-power generation sectors required the methodology, which is described below.

To determine the impacts on GHG emissions occurring from electrification in various energy sectors, emissions must be protected from current levels to the targeted years 2020, 2030, and 2050. Current (2012) GHG emissions for California by source were obtained from the California Greenhouse Gas Emissions Inventory developed by the California Air Resources Board (CARB, 2014).

Growth and control factors were then applied to the current emissions from all major non-power generation sectors to grow emission from 2012 to target years. Factors were determined from the output of the Market Allocation (MARKAL) model, data-intensive energy systems economic optimization model with an EPA developed and maintained nine region database allowing for national and regional energy system characterization. Energy system details embodied in the model framework include primary energy resource supplies, energy conversion technologies, end-use demands, and various technological options to meet specified demands in power generation, residential, commercial, industrial, and transportation sectors in future years. Model outputs include demands, technologies, fuel use and emissions of GHG and pollutants from current to a specified horizon. Figure 59 displays the resulting projections to 2050 by sector of CO_2 emissions for non-power sectors.

Figure 59: Projected annual CO2 emissions by end-use sector for the Base Case



To estimate the reduction from electrification, emission reduction factors applicable in the various scenarios calculated in the modeling methodology were applied to the projected emission total for each sector. Power sector emissions changes from baseline were accounted for and added to each scenario to develop a net estimate of GHG emissions.

3.4 Air Quality Modeling

Tropospheric ozone is a product of photochemistry between NO_X and volatile organic compounds (VOCs) in the ambient atmosphere in the presence of sunlight. In California, NO_X and VOCs are mostly emitted from anthropogenic sources such as on-road and off-road vehicles, power plants and industrial operations, although there are significant biogenic sources of VOCs (CARB, 2009). Ozone concentrations depend on spatial and temporal profiles of precursor emissions, meteorological conditions, transport of precursors and reaction products through, and removal processes such as deposition and chemical reaction. Comprehensive models that incorporate all these physical and chemical processes in detail are widely used to understand and characterize ozone formation on regional scales. These air quality models numerically solve a series of atmospheric chemistry, diffusion, and advection equations in order to determine ambient concentrations of pollutants within control volumes over a given geographic region.

Most models employ an Eulerian representation (one that considers changes as they occur at a fixed location in the fluid, usually called a cell or control volume) of physical quantities on a three-dimensional computational grid. The atmospheric advective diffusion equation for species *m* in a given control volume is:

$$\frac{\partial Q_m^k}{\partial t} = -\nabla \cdot \left(uQ_m^k\right) + \nabla \cdot \left(K\nabla Q_m^k\right) + \left(\frac{Q_m^k}{\partial t}\right)_{sources\,/\,sinks} + \left(\frac{Q_m^k}{\partial t}\right)_{aerosol} + \left(\frac{Q_m^k}{\partial t}\right)_{chemistry} \tag{1}$$

Where *t* is time, *k* is phase (gas or aerosol), u is wind velocity and *K* is the coefficient of eddy diffusivity tensor that parameterizes turbulent diffusion.

The above equation is numerically integrated in time to obtain the concentration, *Q*, of each species *m* in phase *k* (gas phase or aerosol phase), over a series of discrete time steps in each of the spatially distributed discrete cells of the air quality model. Each term on the right side of the advective diffusion equation represents a major process in the atmosphere. From left to right these are: (1) advective transport due to wind, (2) turbulent diffusion due to atmospheric stability/instability, (3) emission (sources) and deposition (sinks), (4) mass transfer between gas and aerosol phases, and (5) chemical reaction.

The outputs from air quality models are spatially and temporally resolved concentrations of pollutant species within control volumes over a geographic region. To minimize the effects of initial conditions, air quality simulations are performed over multiple days and results from the first few days are not included in the analysis.

The air quality model used for this work is the Community Multi-scale Air Quality Model (CMAQ). The CMAQ model (Byun & Ching, 1999) is a comprehensive air quality modeling system developed by the United States Environmental Protection Agency (U.S. EPA) and is used in many regulatory air quality applications such as studying tropospheric ozone, particulate matter, acid deposition and visibility (Appel, et al., 2008) (Appel, et al., 2010) (Foley, et al., 2010). The chemical mechanism used in CMAQ is the CB05 (Luecken, et al., 2008) , which includes the photochemical formation of ozone, oxidation of volatile organic compounds and formation of organic aerosol precursors. For the simulations presented in this report, the spatial resolution of control volumes is 4km × 4km over the entire state, and a vertical height of 10,000 meters above ground, with 30 layers of variable height based on pressure distribution. Meteorological input data for CMAQ was obtained from the Advanced Research Weather Research and Forecasting Model, WRF-ARW (Skamarock, et al., 2005). The National Centers for Environmental Prediction (NCEP) Final Operational Global Analysis 1° × 1° grid data (NCEP , 2005) were used for WRF-ARW initial and boundary conditions.

CHAPTER 4: Results

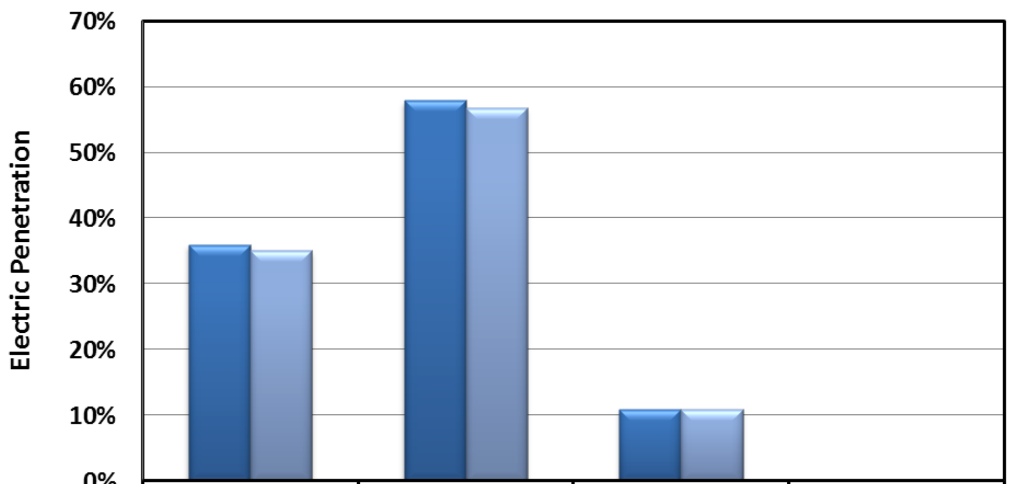
4.1 Final Scenarios

4.1.1 2020 Scenarios

4.1.1.2 2020 Business-As-Usual Base Case (2020 BAU Base Case)

Figure 60 shows the sectoral electric penetrations of 2020 Base Case, which is obtained based on MARKAL projections. Residential and Commercial sectors, which had the highest electric penetrations (36% and 58% respectively) in 2012, are expected to have a small drop in electric penetration. However, industrial sector remains nearly sustained with no change in fuel mix (11%). In contrast, transportation electric penetration nearly doubles from 0.1% in 2012 to 0.2% in 2020.

Figure 60: 2020 BAU Base Case Electric Penetrations

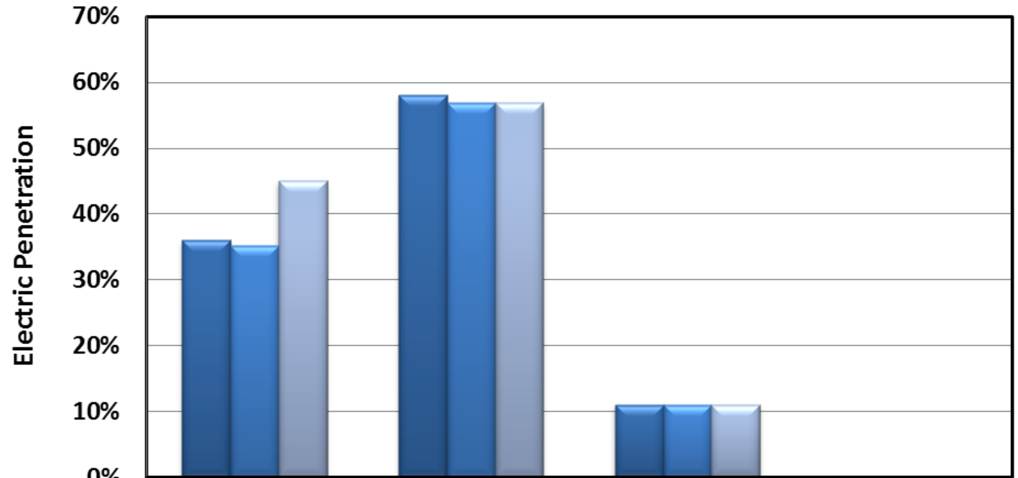


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%

4.1.1.3 2020 Residential Electrification (2020 Res Case)

In this scenario, only residential electrifications are considered; other sectors are assumed to follow business-as-usual projections. As Figure 61 illustrates, electrification is implemented in residential sector by replacing gas-fired heating and cooking devices with state-of-the-art electric technologies. Therefore, electric penetration is forecasted to increase and achieve the target of 45% in 2020.

Figure 61: 2020 Res Case Electric Penetrations

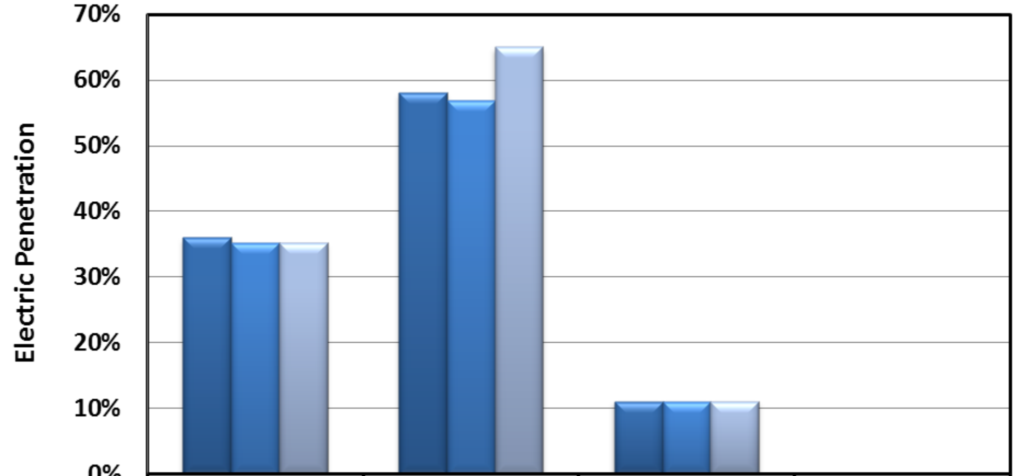


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	45.0%	56.8%	11.0%	0.2%

4.1.1.4 2020 Commercial Electrification (2020 Com Case)

Figure 62 displays the electrification characteristics of 2020 Com Case. In this scenario, electrification is deployed in commercial sector only and there is no enforcement on electrifying other sectors. Electric penetration of commercial sector increases to 65% in 2020 due to electrifying heating and cooking end-uses.

Figure 62: 2020 Com Case Electric Penetrations

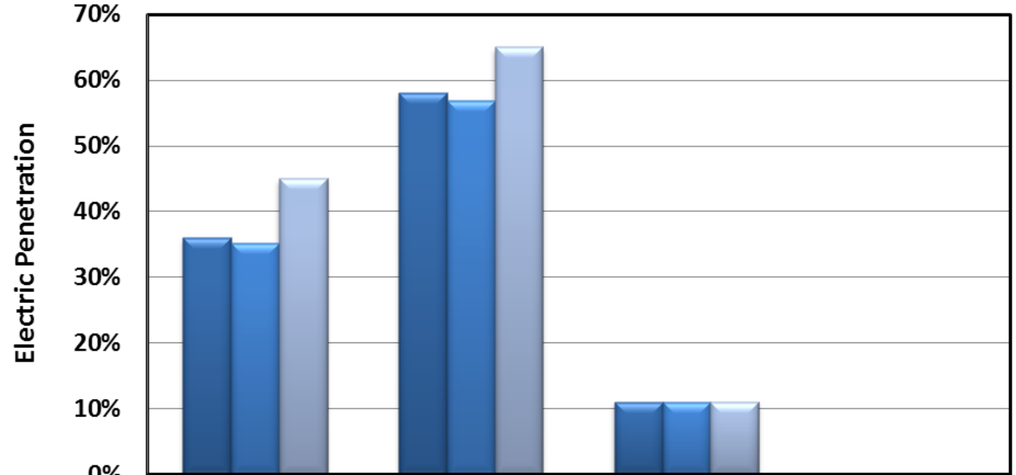


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	35.1%	65.0%	11.0%	0.2%

4.1.1.5 2020 Residential and Commercial Electrification (2020 ResCom Case)

This scenario is combination of 2020 Res and 2020 Com Cases. Residential and commercial sectors are assumed to reach the proposed electric penetration targets (45% and 65% respectively) by 2020 (Figure 63). There is no target for electrifying transportation and industrial sectors; hence, they are assumed to track business-as-usual forecasts.

Figure 63: 2020 ResCom Case Electric Penetrations

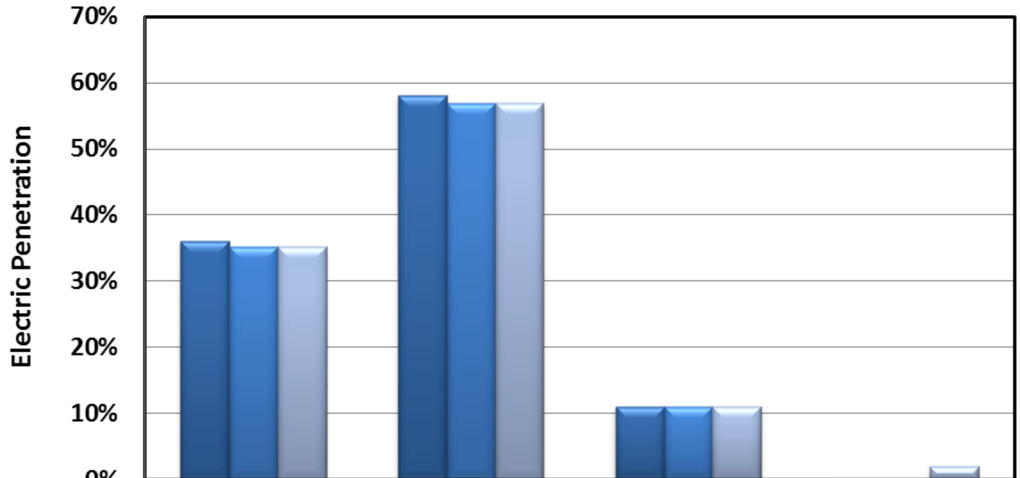


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	45.0%	65.0%	11.0%	0.2%

4.1.1.6 2020 Transportation Electrification (2020 Tra Case)

In this scenario, electrification of transportation sector is implemented via replacing ICE light-duty vehicles with electric vehicles; as Figure 64 illustrates, transportation electrification is enforced so that its electric penetration increases moderately from 0.1% in 2012 to 2% in 2020. Other sectors take no action on electrifying their end-uses; therefore, their electric penetrations are anticipated to follow business-as-usual projections.

Figure 64: 2020 Tra Case Electric Penetrations

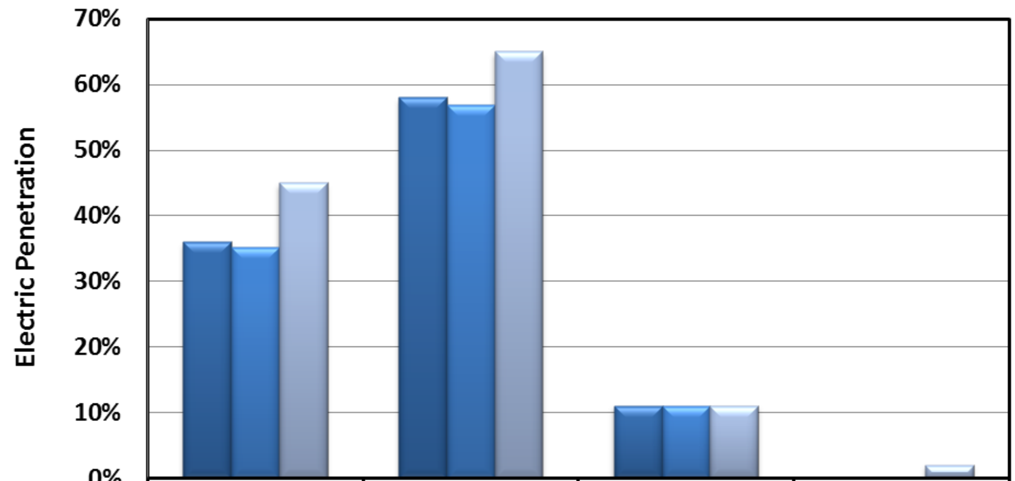


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	35.1%	56.8%	11.0%	2.0%

4.1.1.7 2020 Residential, Commercial, and Transportation Electrification (2020 ResComTra)

This scenario, which is the combination of 2020 Res, 2020 Com, and 2020 Tra cases, implements electrification in all end-use energy sectors excluding the industrial sector. It is assumed that no industrial electrification is performed; however, other sectors are electrified so that electricity, as a fuel, make up a greater portion of their total energy supply. Figure 65 displays the electric penetrations targets of each end-use sector in 2020 ResComTra Case.

Figure 65: 2020 ResComTra Case Electric Penetrations

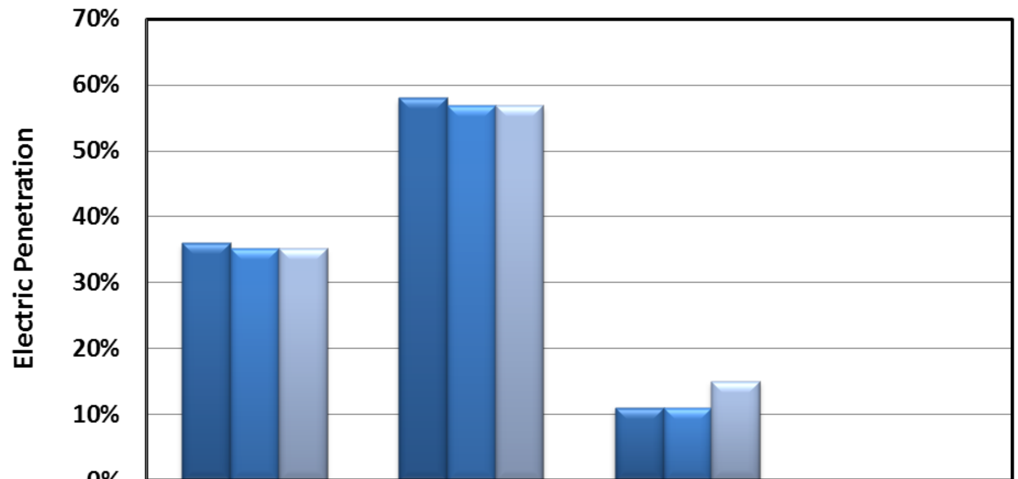


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	45.0%	65.0%	11.0%	2.0%

4.1.1.8 2020 Industrial Electrification (2020 Ind)

In contrast to 2020 ResComTra Case, this scenario only enforces industrial electrification; the electric penetration of industrial sector slightly increase from 11% in 2012 to 15% in 2020 (Figure 66). Industrial electrification is implemented mainly via replacement of gas-fired boilers with state-of-the-art electric boilers. Other sectors are assumed to sustain their fuel mix, with following business-as-usual trends.

Figure 66: 2020 Ind Case Electric Penetrations

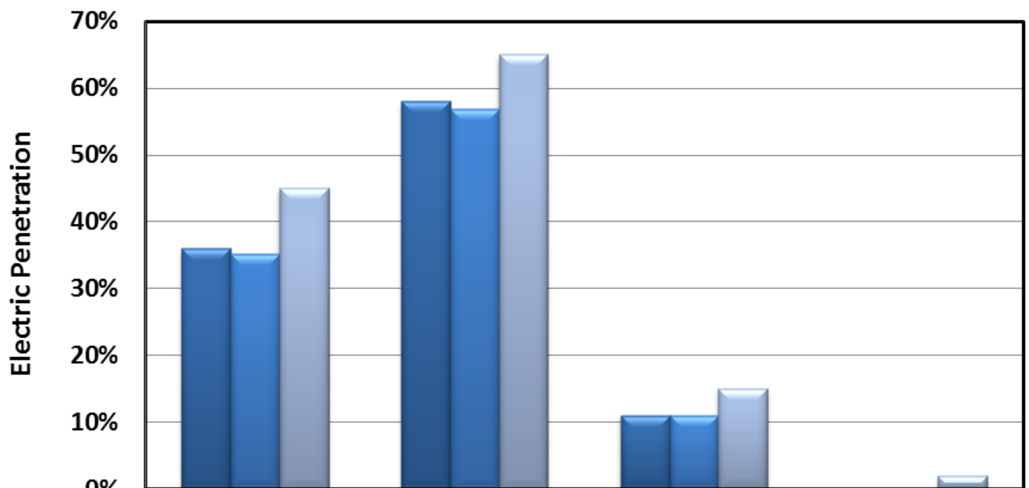


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	35.1%	56.8%	15.0%	0.2%

4.1.1.9 2020 All Sectors Electrification (2020 ResComTraInd)

This scenario is simultaneous deployment of electrification in all end-use energy sectors. As Figure 67 display, residential and commercial sectors are set to achieve the electric penetration target of 45% and 65%, respectively, by 2020, which is performed through electrifying heating and cooking end-uses. Electric penetration of industrial sector increases moderately to 15% via replacing gas-fired boilers with electric boilers, while transportation electrification is implemented only in light-duty vehicles, which increases the electric penetration from 0.1% in 2012 to 2% in 2020.

Figure 67: 2020 ResComTraInd Case Electric Penetrations



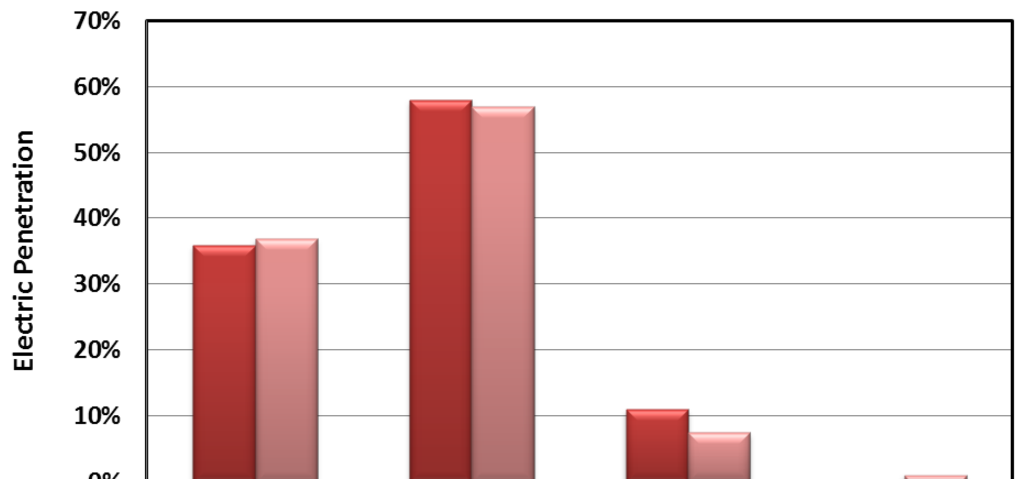
	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2020 BAU	35.1%	56.8%	11.0%	0.2%
2020	45.0%	65.0%	15.0%	2.0%

4.1.2 2030 Scenarios

4.1.2.1 2030 Business-As-Usual Base Case (2030 BAU Base Case)

Figure 68 shows the sectoral electric penetrations of 2030 Base Case, which is obtained based on MARKAL projections. Commercial sector, which had the highest electric penetration (58%) in 2012, is expected to have a slight decrease in electric penetration. In contrast, electric penetrations of residential and industrial sectors drop, mainly due to lower prices of fossil fuels in 2030. Based on MARKAL projections, electric penetration of transportation sector increases from 0.1% in 2012 to 1.1% in 2030.

Figure 68: 2030 BAU Base Case Electric Penetrations

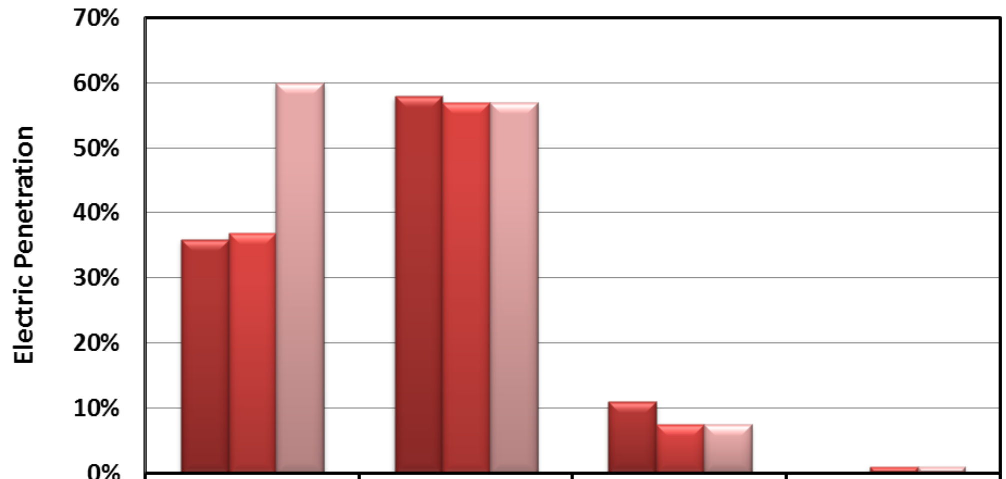


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%

4.1.2.3 2030 Residential Electrification (2030 Res Case)

In this scenario, only residential electrifications is considered; other sectors are assumed to follow business-as-usual projections. As Figure 69 illustrates, electrification is implemented in residential sector by replacing gas-fired heating and cooking devices with state-of-the-art electric technologies. Therefore, electric penetration is forecasted to increase and achieve the target of 60% in 2030.

Figure 69: 2030 Res Case Electric Penetrations

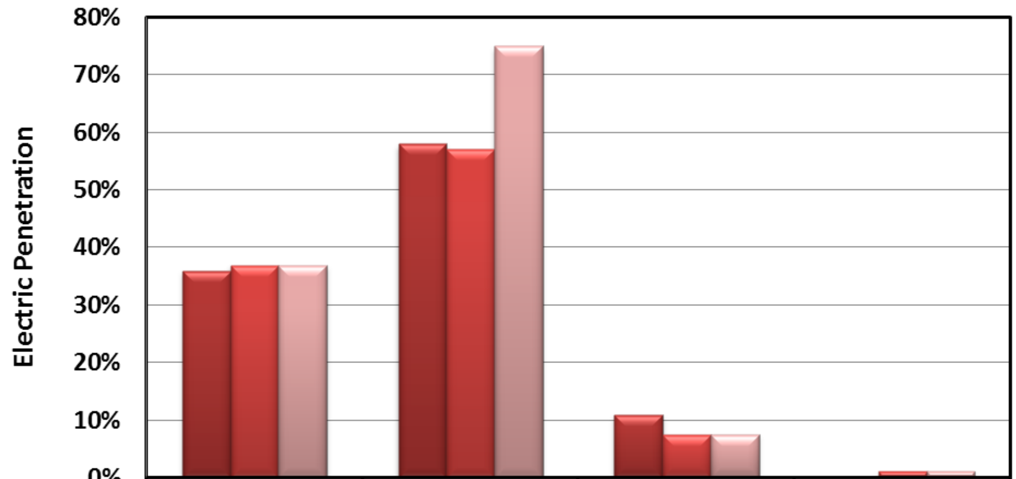


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	60.0%	57.0%	7.5%	1.1%

4.1.2.4 2030 Commercial Electrification (2030 Com Case)

Figure 70 displays the electrification characteristics of 2030 Com Case. In this scenario, electrification is deployed in commercial sector only and there is no enforcement on electrifying other sectors. Electric penetration of commercial sector increases to 75% in 2030 due to electrifying heating and cooking end-uses.

Figure 70: 2030 Com Case Electric Penetrations

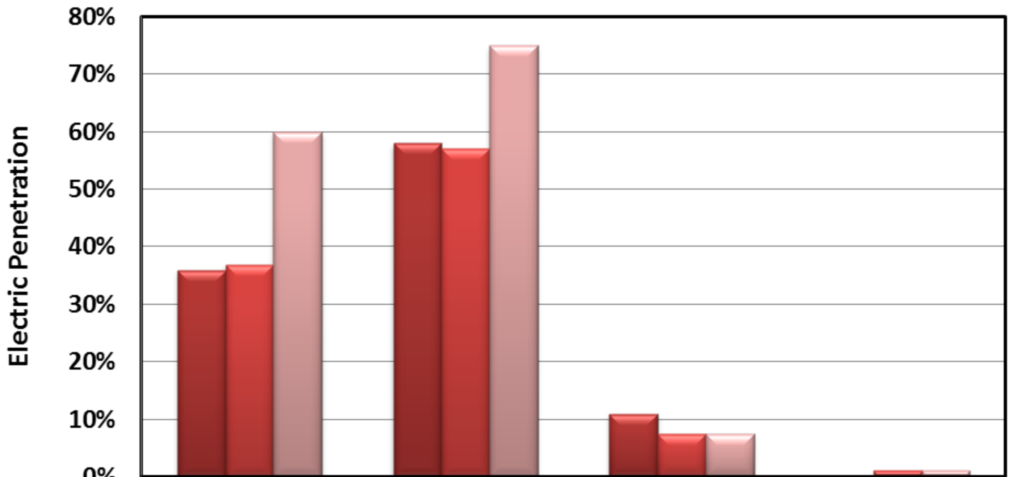


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	36.9%	75.0%	7.5%	1.1%

4.1.2.5 2030 Residential and Commercial Electrification (2030 ResCom)

This scenario is combination of 2030 Res and 2030 Com Cases. Residential and commercial sectors are assumed to reach the proposed electric penetration targets (60% and 75% respectively) by 2020 (Figure 71). There is no target for electrifying transportation and industrial sectors; hence, they are assumed to track business-as-usual forecasts.

Figure 71: 2030 ResCom Case Electric Penetrations

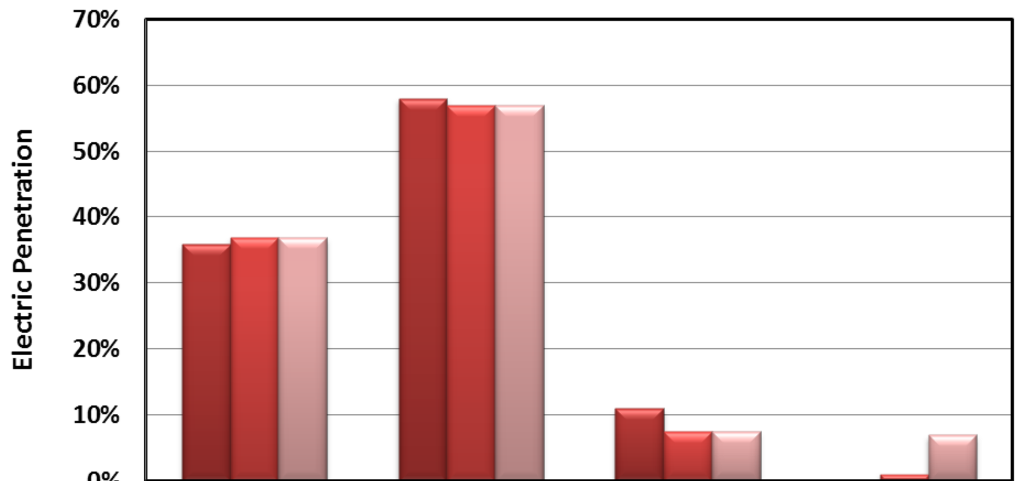


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	60.0%	75.0%	7.5%	1.1%

4.1.2.6 2030 Immediate Transportation Electrification (2030 Immediate Tra Case)

In this scenario, electrification of transportation sector is implemented via replacing ICE light-duty vehicles with electric vehicles; as Figure 72 illustrates, transportation electrification is enforced so that its electric penetration increases moderately from 0.1% in 2012 to 7% in 2020. All electric vehicles are assumed to charge with immediate charging strategy. Other sectors take no action on electrifying their end-uses; therefore, their electric penetrations are anticipated to follow business-as-usual projections.

Figure 72: 2030 Immediate Tra Case Electric Penetrations



	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	36.9%	57.0%	7.5%	7.0%

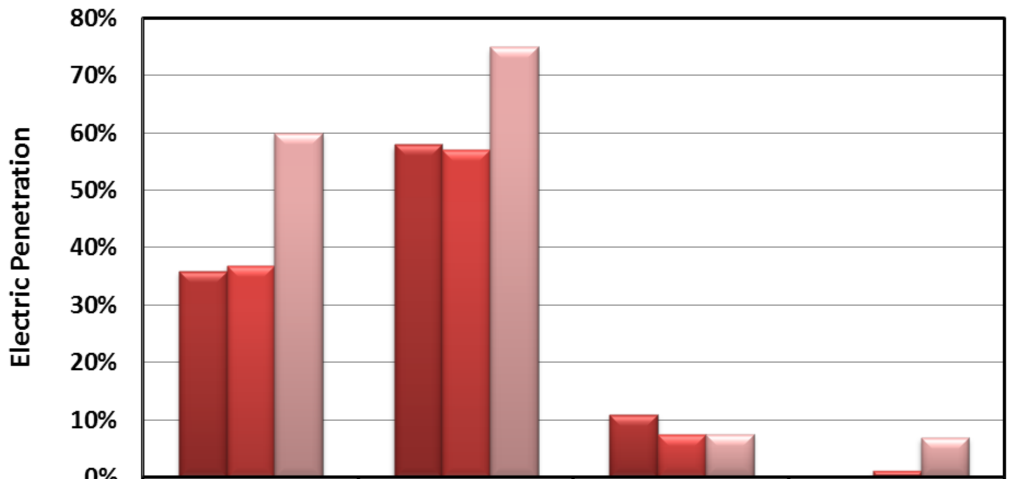
4.1.2.7 2030 Smart Transportation Electrification (2030 Immediate Tra Case)

Similar to immediate transportation scenario, transportation sector is electrified via replacing ICE light-duty vehicles with battery electric vehicles; however, electric vehicles are charged with smart charging strategy instead. Transportation electrification is enforced so that its electric penetration increases moderately from 0.1% in 2012 to 7% in 2020. Other sectors are anticipated to follow business-as-usual trends.

4.1.2.8 2030 Residential, Commercial, and Transportation Electrification (2030 ResComTra)

This scenario, which is the combination of 2030 Res, 2030 Com, and 2030 Tra cases, implements electrification in all end-use energy sectors excluding the industrial sector. It is assumed that no industrial electrification is performed; however, other sectors are electrified so that electricity, as a fuel, make up a greater portion of their total energy supply. Figure 73 displays the electric penetrations targets of each end-use sector in 2030 ResComTra Case.

Figure 73: 2030 ResComTra Case Electric Penetrations

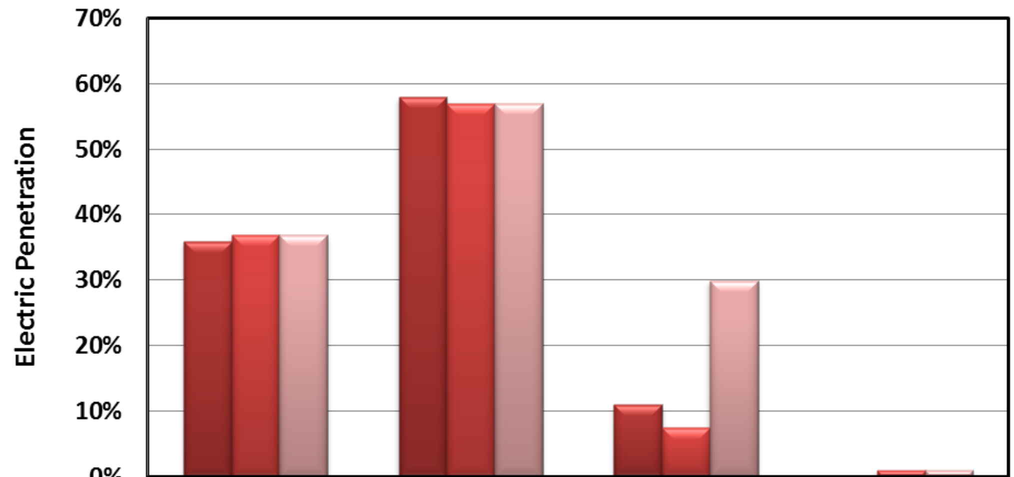


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	60.0%	75.0%	7.5%	7.0%

4.1.2.9 2030 Industrial Electrification (2030 Ind)

In contrast to 2030 ResComTra Case, this scenario only enforces industrial electrification; the electric penetration of industrial sector increase from 11% in 2012 to 30% in 2030 (Figure 74). Industrial electrification is implemented mainly via replacement of gas-fired boilers with state-of-the-art electric boilers. Other sectors are assumed to sustain their fuel mix, with following business-as-usual trends.

Figure 74: 2030 Ind Case Electric Penetrations

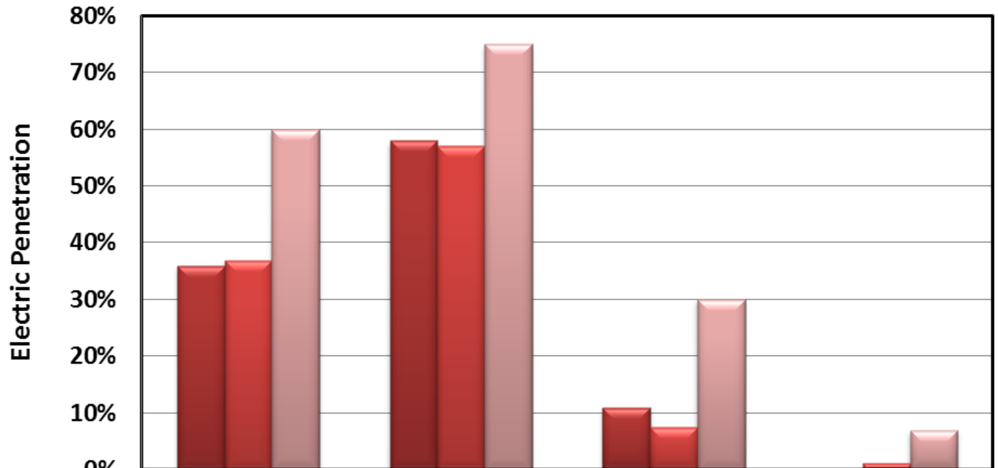


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	36.9%	57.0%	30.0%	1.1%

4.1.2.10 2030 All Sectors Electrification (2030 ResComTraInd)

This scenario is simultaneous deployment of electrification in all end-use energy sectors. As Figure 75 display, residential and commercial sectors are set to achieve the electric penetration target of 60% and 75%, respectively, by 2030, which is performed through electrifying heating and cooking end-uses. Electric penetration of industrial sector increases to 30% via replacing gas-fired boilers with electric boilers, while transportation electrification is implemented only in light-duty vehicles, which increases the electric penetration from 0.1% in 2012 to 7% in 2030.

Figure 75: 2030 ResComTraInd Case Electric Penetrations



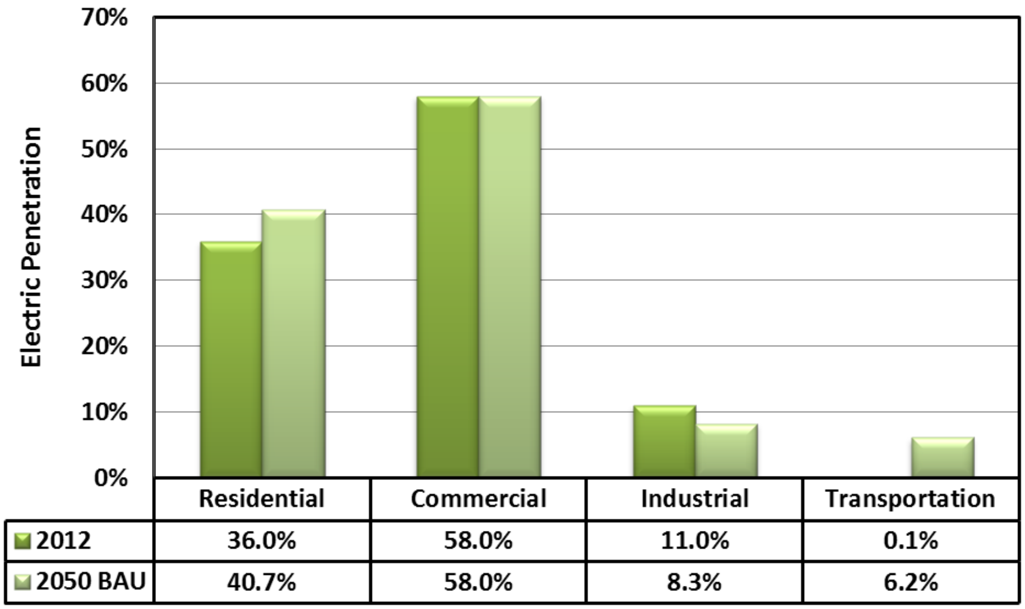
	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2030 BAU	36.9%	57.0%	7.5%	1.1%
2030	60.0%	75.0%	30.0%	7.0%

4.1.3 2050 Scenarios

4.1.3.1 2050 Business-As-Usual Base Case (2050 BAU Base Case)

Figure 76 shows the sectoral electric penetrations of 2050 Base Case, which is obtained based on MARKAL projections. Commercial sector, which had the highest electric penetration (58%) in 2012, is expected maintain its 2012 fuel mix. Following business-as-usual trends, electric penetration of residential sector increases from 36% in 2012 to 40.7% in 2050. In contrast, electric penetrations of industrial sector drops, mainly due to lower prices of fossil fuels in 2050. Based on MARKAL projections, electric penetration of transportation sector increases from 0.1% in 2012 to 6.2% in 2050.

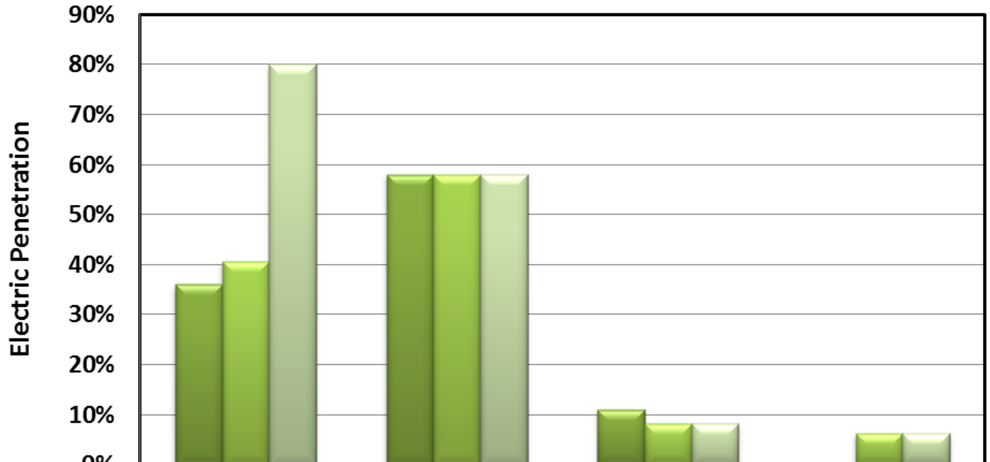
Figure 76: 2050 BAU Base Case Electric Penetrations



4.1.3.2 2050 Residential Electrification (2050 Res Case)

In this scenario, only residential electrifications is considered; other sectors are assumed to follow business-as-usual projections. As Figure 77 illustrates, electrification is implemented in residential sector by replacing gas-fired heating and cooking devices with state-of-the-art electric technologies. Therefore, electric penetration is forecasted to increase and achieve the target of 80% in 2050.

Figure 77: 2050 Res Case Electric Penetrations

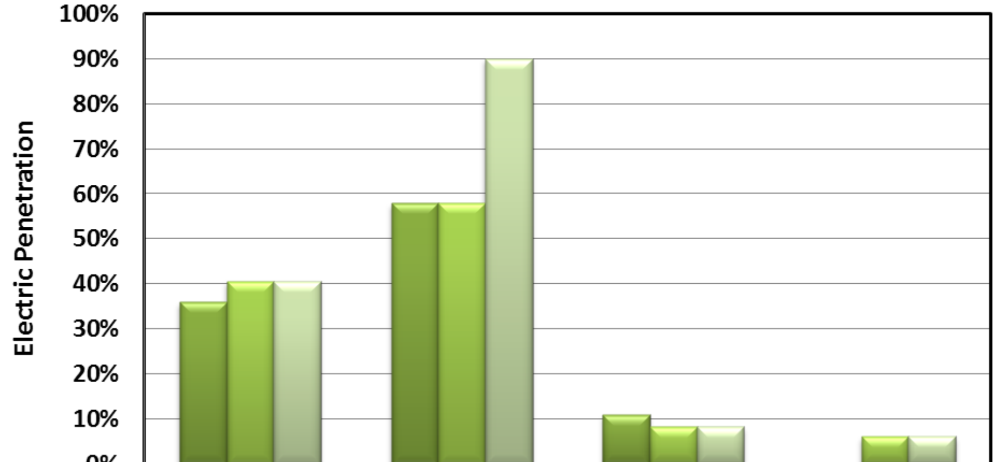


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	80.0%	58.0%	8.3%	6.2%

4.1.3.3 2050 Commercial Electrification (2050 Com)

Figure 78 displays the electrification characteristics of 2050 Com Case. In this scenario, electrification is deployed in commercial sector only and there is no enforcement on electrifying other sectors. Electric penetration of commercial sector increases to 90% in 2050 due to electrifying heating and cooking end-uses.

Figure 78: 2050 Com Case Electric Penetrations

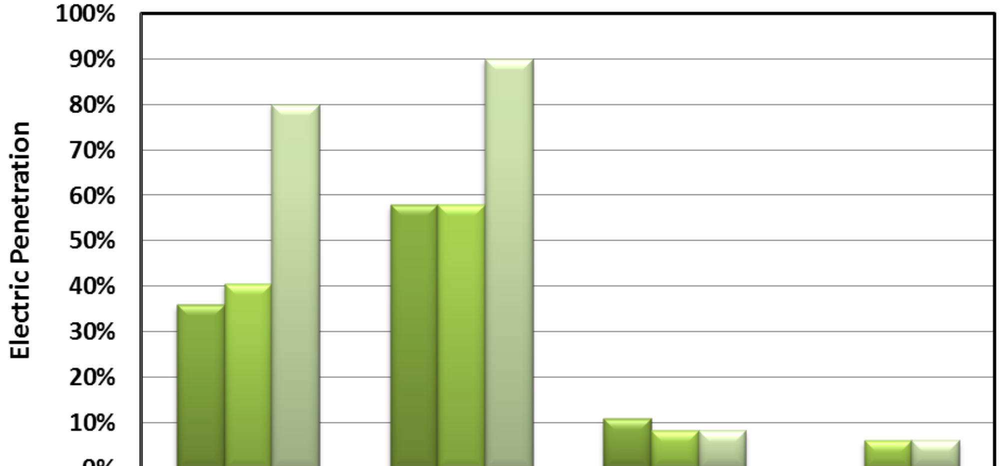


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	40.7%	90.0%	8.3%	6.2%

4.1.3.4 2050 Residential and Commercial Electrification (2050 ResCom)

This scenario is combination of 2050 Res and 2050 Com Cases. Residential and commercial sectors are assumed to reach the proposed electric penetration targets (80% and 90% respectively) by 2050 (Figure 79). There is no target for electrifying transportation and industrial sectors; hence, they are assumed to track business-as-usual forecasts.

Figure 79: 2050 ResCom Case Electric Penetrations

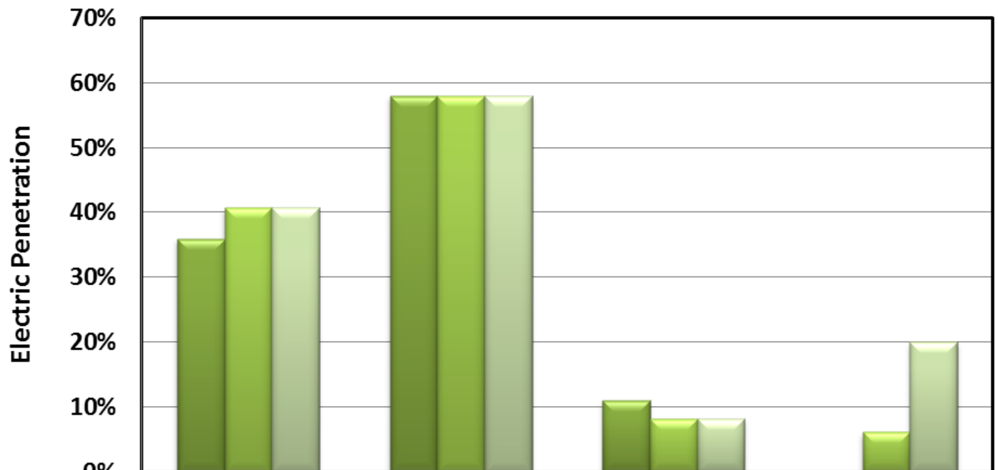


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	80.0%	90.0%	8.3%	6.2%

4.1.3.5 2050 Transportation Electrification (2050 Tra)

In this scenario, electrification of transportation sector is implemented via replacing ICE light-duty vehicles with electric vehicles; as Figure 80 illustrates, transportation electrification is enforced so that its electric penetration increases moderately from 0.1% in 2012 to 20% in 2050. Other sectors take no action on electrifying their end-uses; therefore, their electric penetrations are anticipated to follow business-as-usual projections.

Figure 80: 2050 Tra Case Electric Penetrations



	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	40.7%	58.0%	8.3%	20.0%

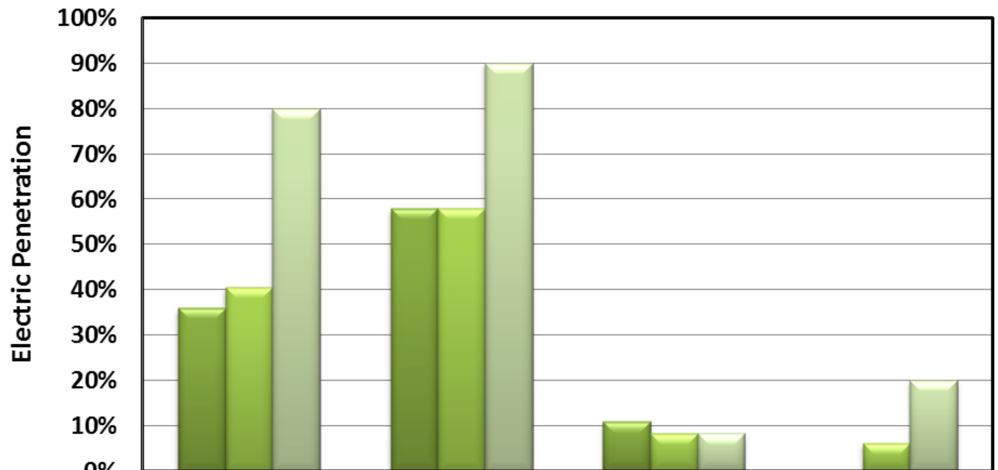
4.1.3.6 2050 Smart Transportation Electrification (2050 Immediate Tra Case)

Similar to immediate transportation scenario, transportation sector is electrified via replacing ICE light-duty vehicles with battery electric vehicles; however, electric vehicles are charged with smart charging strategy instead. Transportation electrification is enforced so that its electric penetration increases from 0.1% in 2012 to 20% in 2050. Other sectors are anticipated to follow business-as-usual trends.

4.1.3.7 2050 Residential, Commercial, and Transportation Electrification (2050 ResComTra)

This scenario, which is the combination of 2050 Res, 2050 Com, and 2050 Tra cases, implements electrification in all end-use energy sectors excluding the industrial sector. It is assumed that no industrial electrification is performed; however, other sectors are electrified so that electricity, as a fuel, make up a greater portion of their total energy supply. Figure 81 displays the electric penetrations targets of each end-use sector in 2050 ResComTra Case.

Figure 81: 2050 ResComTra Case Electric Penetrations

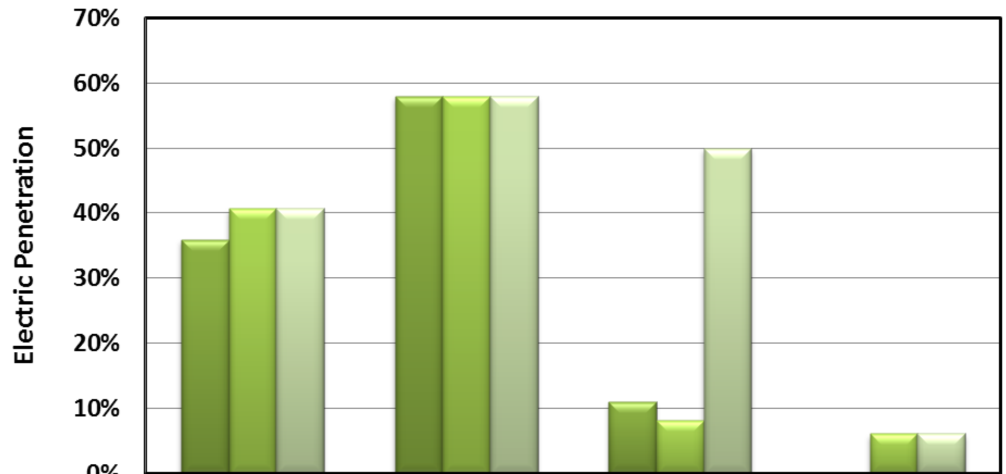


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	80.0%	90.0%	8.3%	20.0%

4.1.3.8 2050 Industrial Electrification (2050 Ind)

In contrast to 2050 ResComTra Case, this scenario only enforces industrial electrification; the electric penetration of industrial sector increase from 11% in 2012 to 50% in 2050 (Figure 82). Industrial electrification is implemented mainly via replacement of gas-fired boilers with state-of-the-art electric boilers. Other sectors are assumed to sustain their fuel mix, with following business-as-usual trends.

Figure 82: 2050 Ind Case Electric Penetrations

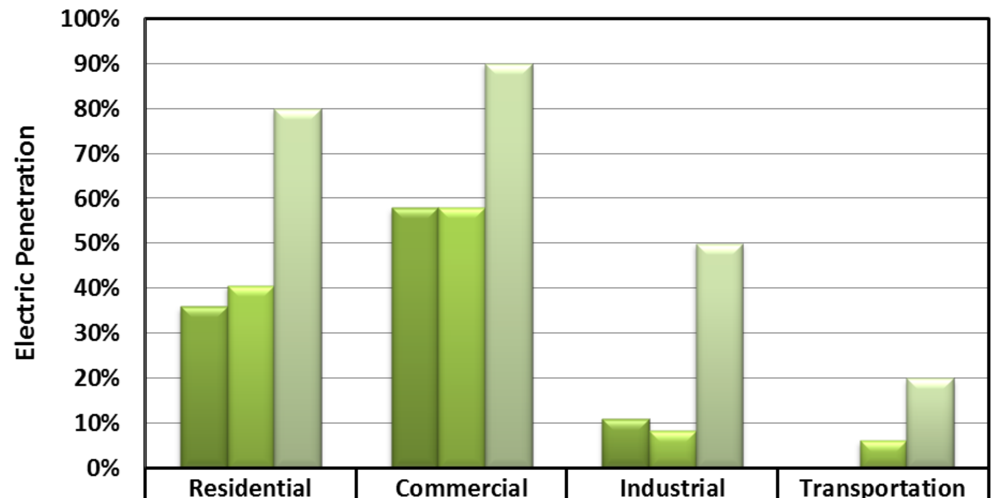


	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	40.7%	58.0%	50.0%	6.2%

4.1.3.9 2050 All Sectors Electrification (2050 ResComTraInd)

This scenario is simultaneous deployment of electrification in all end-use energy sectors. As Figure 83 display, residential and commercial sectors are set to achieve the electric penetration target of 80% and 90%, respectively, by 2050, which is performed through electrifying heating and cooking end-uses. Electric penetration of industrial sector increases to 50% via replacing gas-fired boilers with electric boilers, while transportation electrification is implemented only in light-duty vehicles, which increases the electric penetration from 0.1% in 2012 to 20% in 2030.

Figure 83: 2050 ResComTraInd Case Electric Penetrations



	Residential	Commercial	Industrial	Transportation
2012	36.0%	58.0%	11.0%	0.1%
2050 BAU	40.7%	58.0%	8.3%	6.2%
2050	80.0%	90.0%	50.0%	20.0%

4.2 Grid Impacts

4.2.1 Electrification Load

4.2.1.1 Electrification Load Profile of 2020 Scenarios

Figure 84 compare the electrification load profile of 2020 scenarios in a summer week (July 6th – July 18th). Industrial electrification scenario introduces a flat load addition of nearly 2 GW to the grid, since industrial sector operates constantly 24 hours a day and seven days a week. The commercial electrification case presents the lowest load intermittencies to the grid due to fairly smooth demand throughout the day, while electrification load profile of residential case is quite intermittent due to high demand for water heating, and cooking in early morning and evening. However, the residential scenario introduces the lowest additional load to the grid since there is no space heating demand in summer. The transportation scenario is far more intermittent compared to other individual sector electrification cases, which is mainly due to huge demand for immediate charging of electric vehicles in the evening. As expected, the all sectors electrification scenario has the largest electrification load, with a peak demand of nearly 13.5 GW in summer, which is due to the aggregate electrification impact of individual sectors.

Figure 84: Electrification Load Comparison - Summer 2020

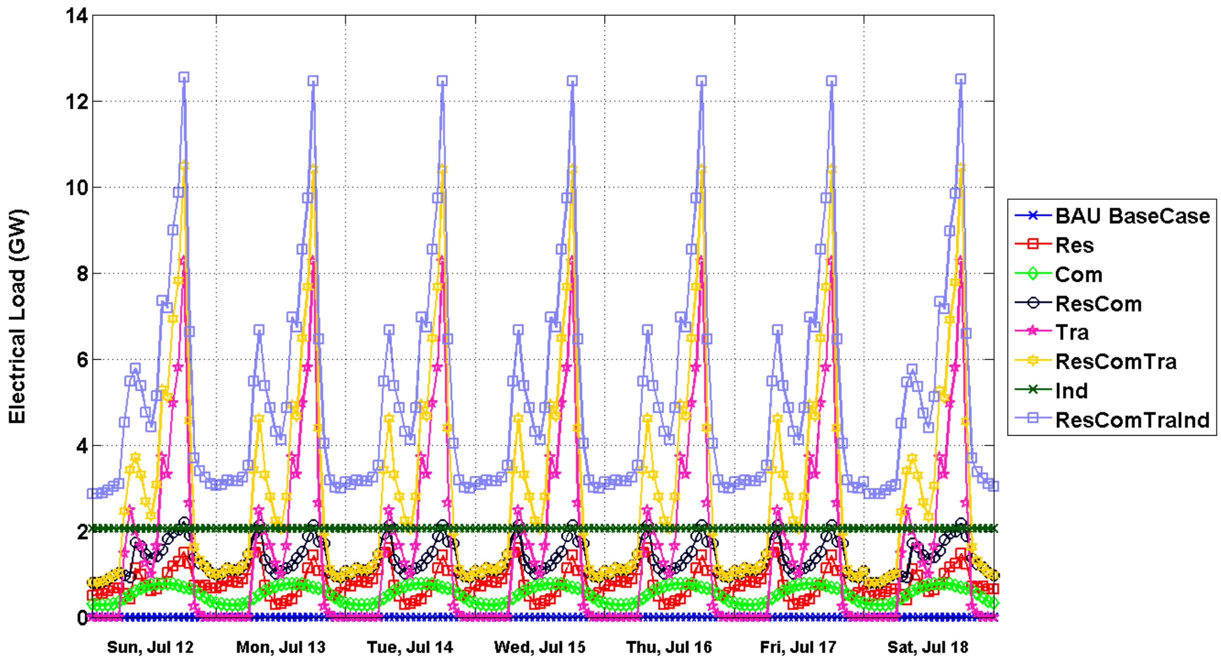
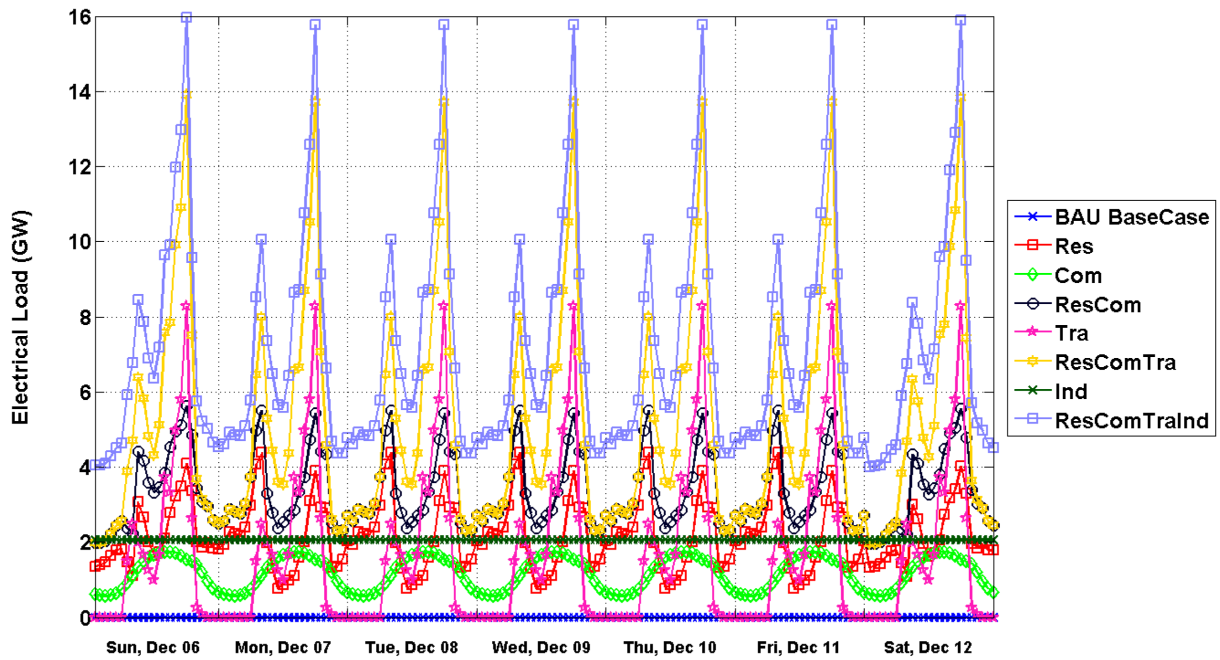


Figure 85 compare the electrification load profile of 2020 scenarios in a winter week (December 6th to December 12th). Similar to summer electrification load profiles, Industrial electification load is flat due to 24/7 demand, while transportaion electrification introduces a huge spike into the grid as a result of intense immediate charging of electric vehicles in the evenings. The electrification load shapes of summer and winter weeks are quite similar; however, the magnitude of winter electrification loads in scenarios that include residential or commercial sectors, are higher because of greater space heating demand in winter.

Figure 85: Electrification Load Comparison - Winter 2020



4.2.1.2 Electrification Load Profile of 2030 Scenarios

Figures 86 and 87 show the hourly electrification load profile of summer and winter for 2030 scenarios. The load characterstics are similar to those of 2020 scenarios. However the magnitudes of electrification loads are significantly larger due to higher sectoral electric penetration targets. For example, the immediate transportation case presents nearly 25 GW of additional power to the demand in summer 2030, while only 9 GW of excess load is added due to transportation electrification in 2020. As would be expected, the all sectors case has the largest electrification load with demanding approximately 40 GW of additional electric power in summer.

Figure 86: Electrification Load Comparison - Summer 2030

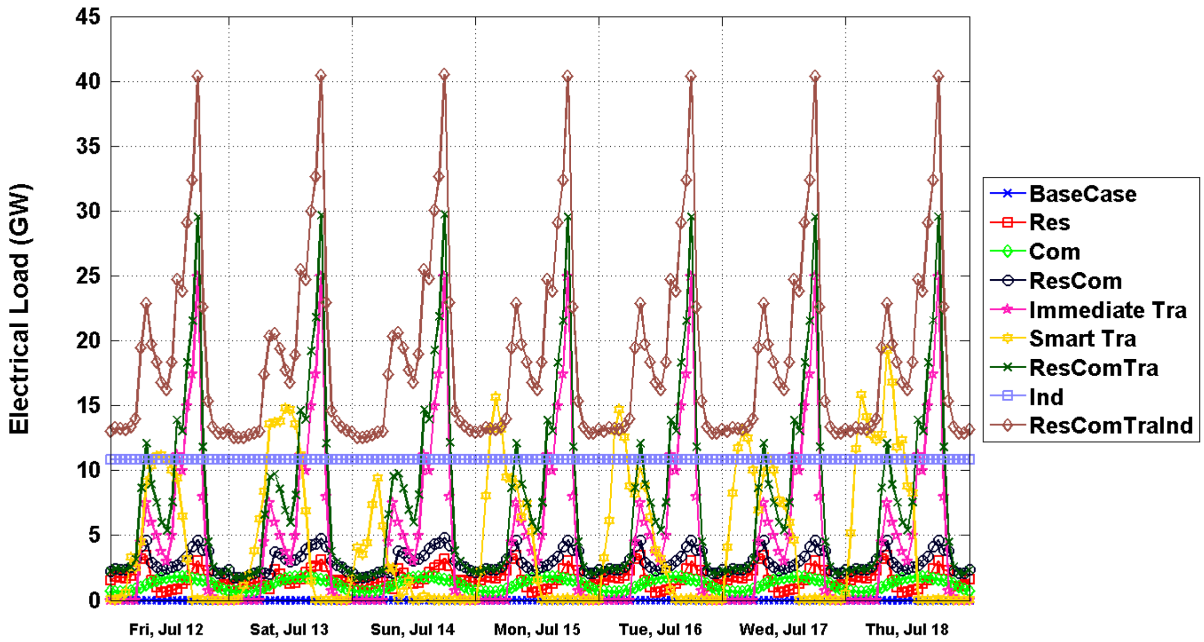
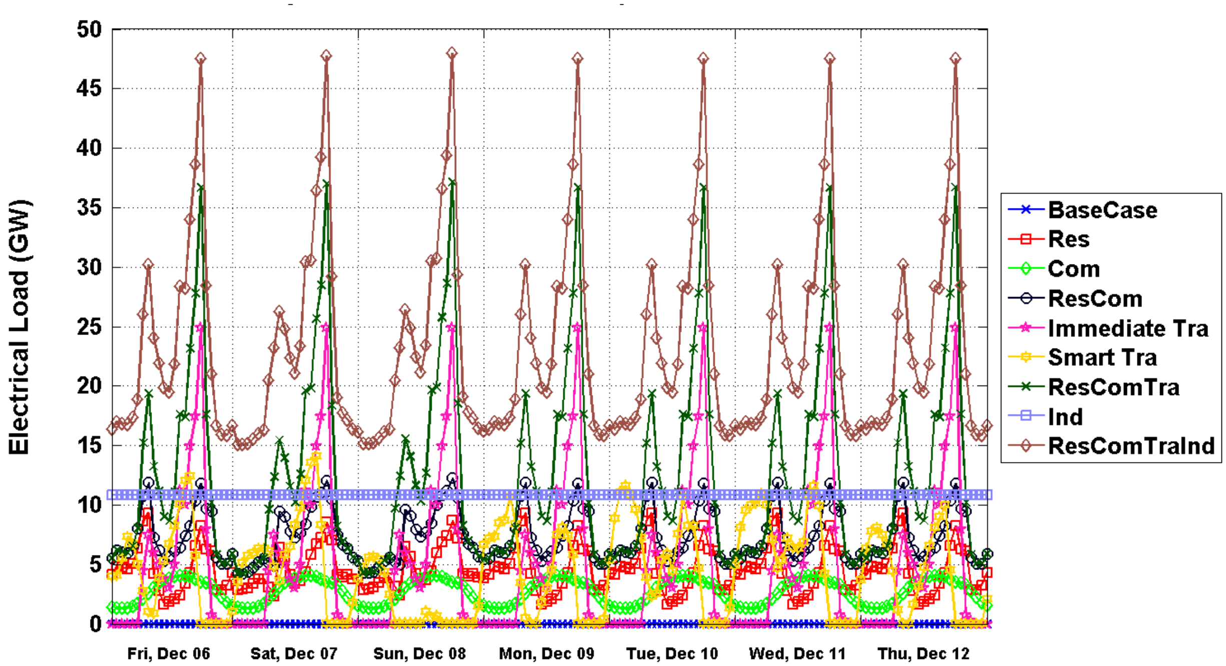


Figure 87: Electrification Load Comparison - Winter 2030



4.2.1.3 Electrification Load Profile of 2050 Scenarios

Figure 88 and 89 show the hourly electrification load profile of summer and winter weeks for 2050 scenarios. The load characterstics are similar to those of 2020, and 2030 scenarios. However the magnitudes of electrification loads are significantly larger due to higher sectoral electric penetration targets. Non-transportation scenarios – including 2050 Res, 2050 Com and 2050 Ind Cases – introduce less than 25 GW of additional peak power to the grid, while transportation electrification scenarios reach peak powers as high as 65 GW. This is mainly due to highly-intermittent transportation demand, which results from immediate charging of electric vehicles in the evenings. The peak power demand of smart transportation case is lower (48 GW) due to high flexibility of smart charging strategy, which improves grid dynamics.

Figure 88: Electrification Load Comparison - Summer 2050

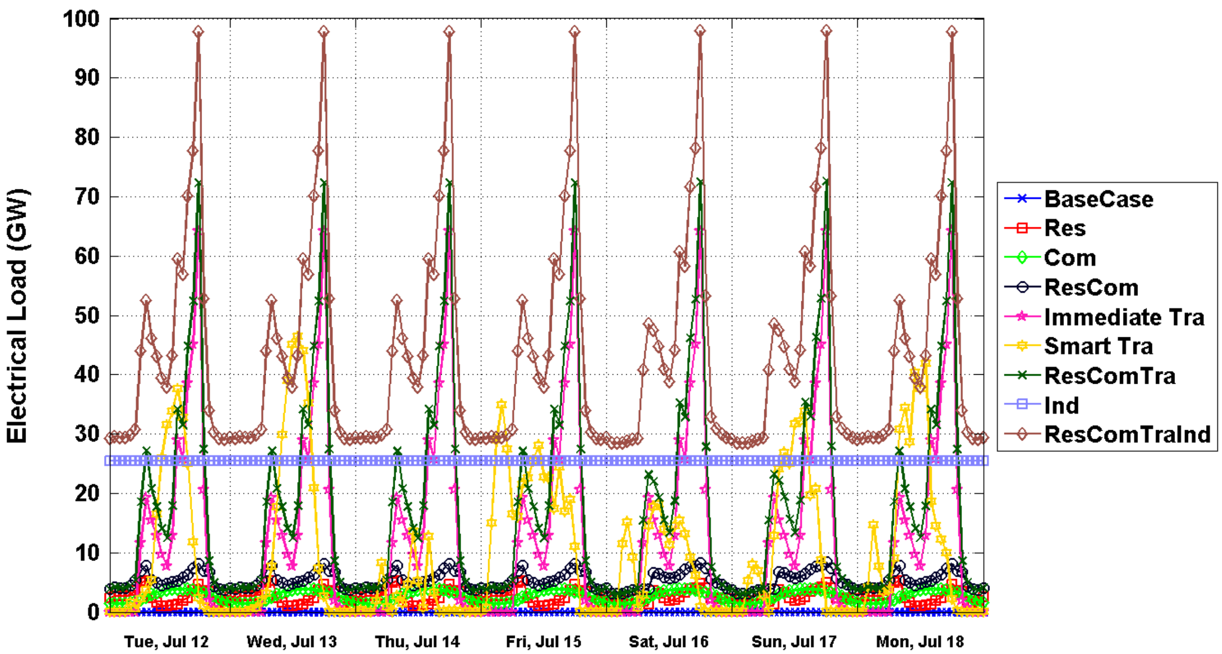
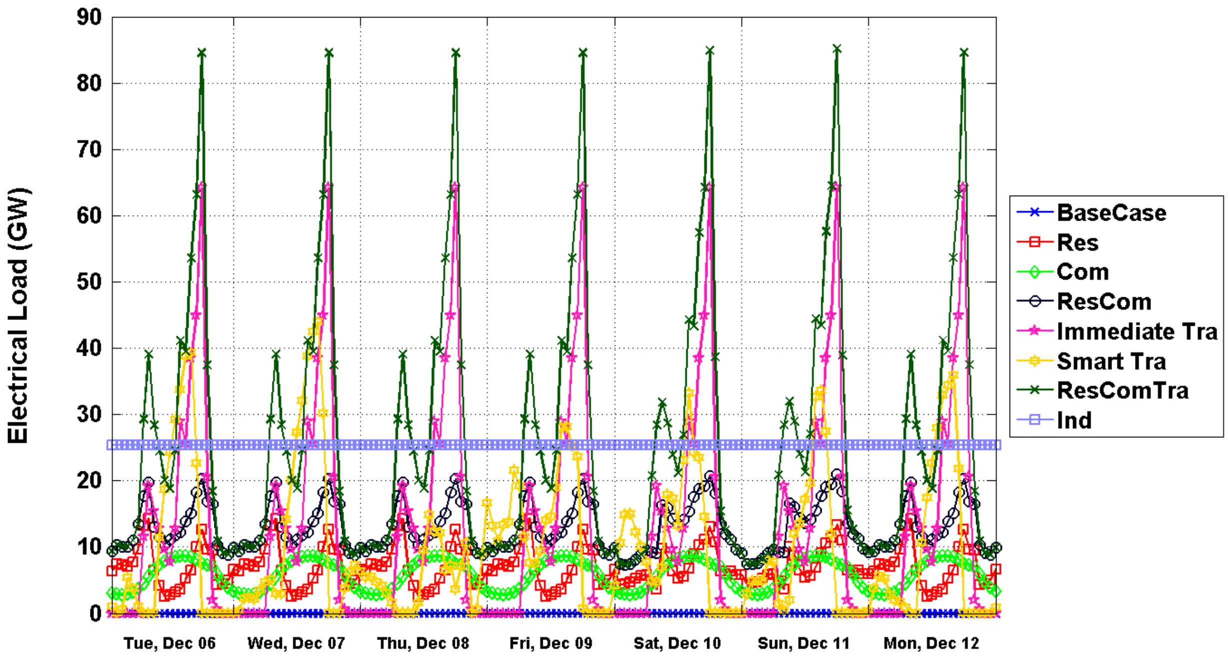


Figure 89: Electrification Load Comparison - Winter 2050



4.2.2 Statewide Electricity Demand

4.2.2.1 Electricity Demand Profile of 2020 Scenarios

Figure 90 and 91 display the hourly statewide electricity demand of summer and winter for 2020 scenarios. The Base Case scenario has a peak power demand of nearly 63 GW in summer and 42 GW in winter. The additional electricity loads, due to electrification of buildings and industrial scenarios, are less than 2 GW in summer and 6 GW in winter. In addition, these scenarios neither introduce further intermittency to the original demand, nor they smooth out the existing flucatuations in the grid due to moderatly smooth demands. The peak power demand of these scenarios do not exceed 73 GW in summer and 60 GW in winter. In contrast, the transportation scenario not only adds load peaks as high as 9 GW to the original demand, but it also worsen the evening peak with coincident immediate charging of electric vehicles.

Figure 90: Statewide Electricity Demand Comparison - Summer 2020

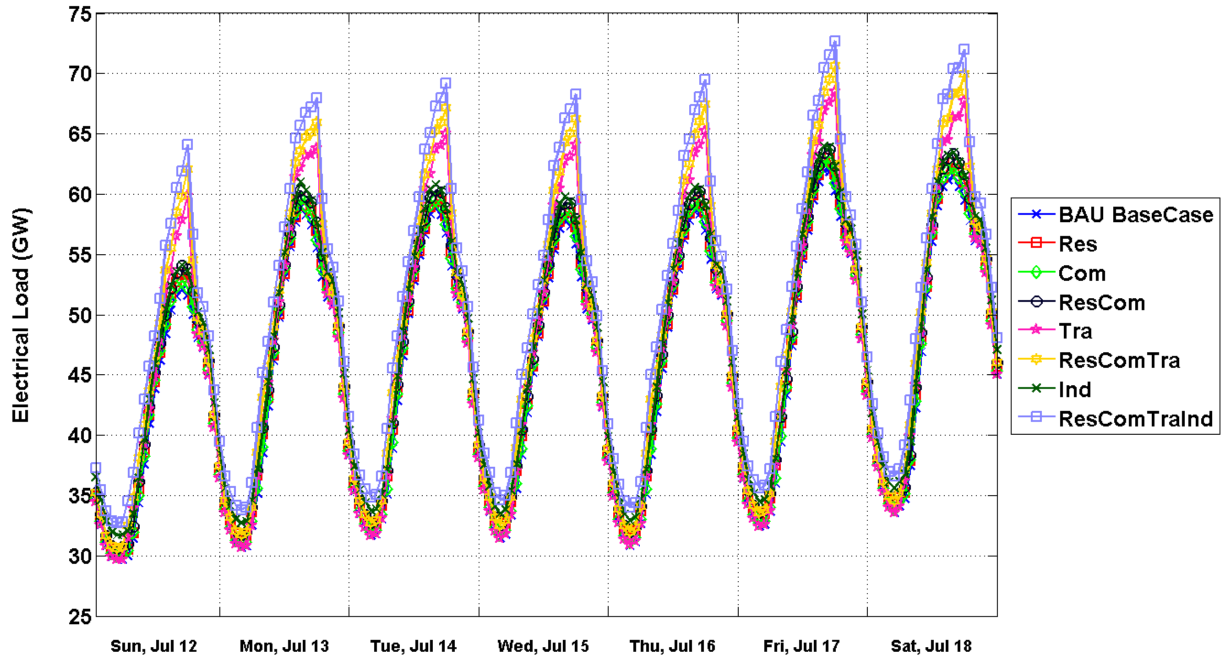
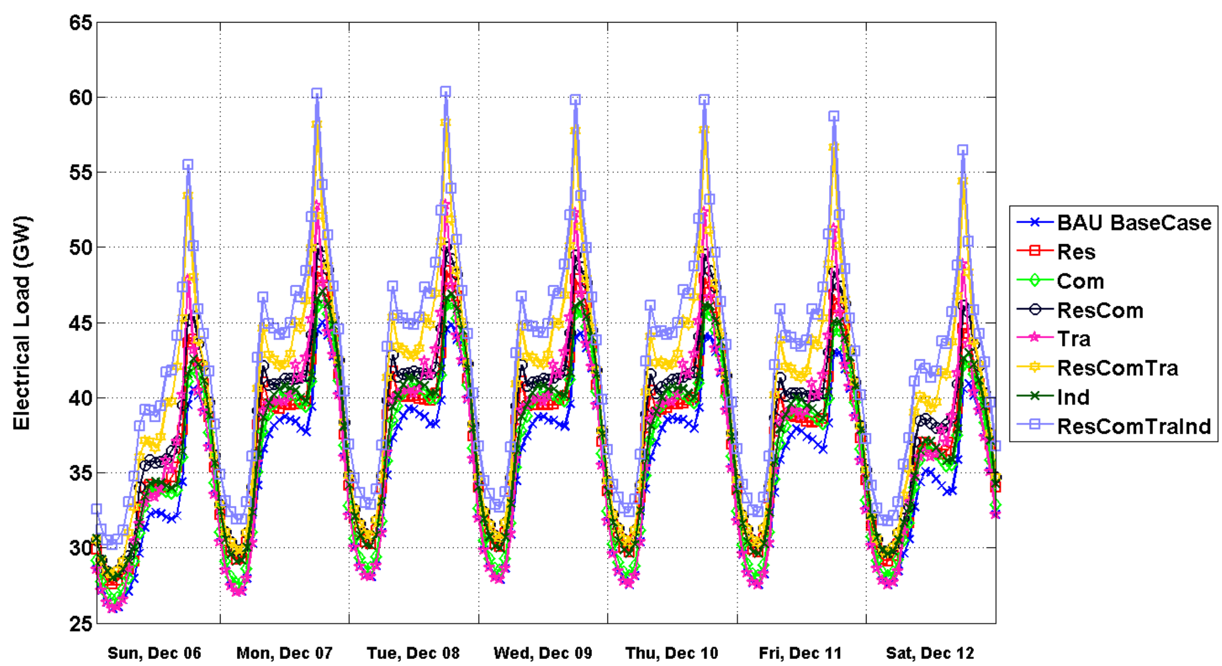


Figure 91: Statewide Electricity Demand Comparison - Winter 2020



4.2.2.2 Electricity Demand Profile of 2030 Scenarios

Figure 92 and 93 show the hourly statewide electricity demand of summer and winter for 2030 scenarios. 2030 Base Case has a peak power demand of nearly 70 GW in summer and 50 GW in winter. The peak power demand of non-transportation scenarios do not exceed than 80 GW in summer and 63 GW in winter. In contrast, the power demand of transportaion scenarios can be as high as 108 GW in Winter and 97 GW in Summer, which requires higher installed capacity of power resources, compared to the base case. The smart charging scenario adds a huge peak load of nearly 20 GW, increasing the statewide demand peak to 90 GW in summer and 70 GW in winter. However, this peak occurs around noon when significant solar power is available, increasing absorption of renewable energy, while minimizing additional demand to power plants. The All Sectors scenario achieve a peak demand of about 108 GW in summer and 97 GW in winter.

Figure 92: Statewide Electricity Demand Comparison - Summer 2030

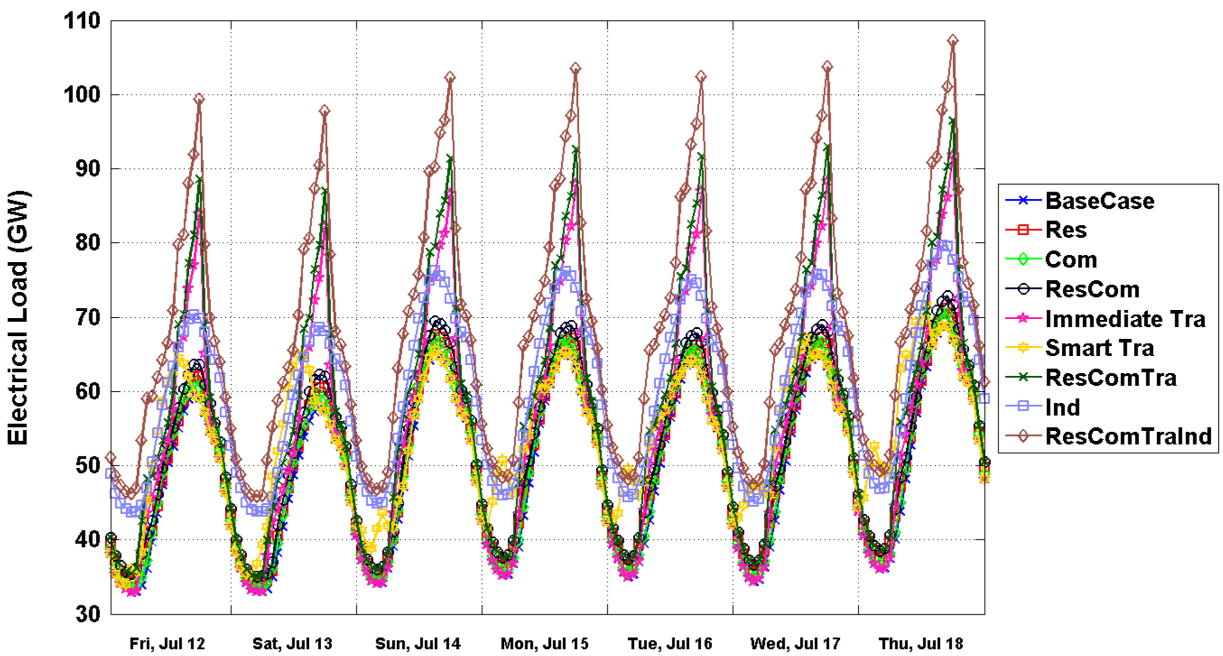
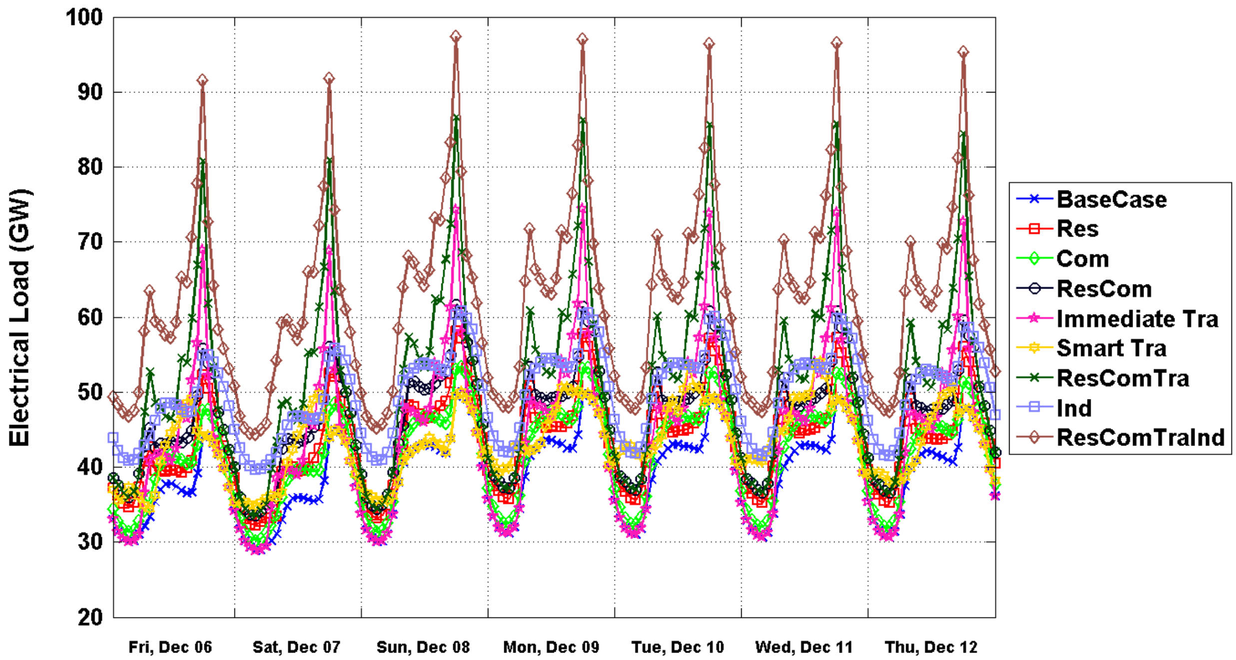


Figure 93: Statewide Electricity Demand Comparison - Winter 2030



4.2.2.3 Electricity Demand Profile of 2050 Scenarios

Figure 94 and 95 show the statewide electricity demand of summer and winter for 2050 scenarios. 2050 Base Case has a peak power demand of nearly 80 GW in summer and 55 GW in winter. The peak power demand of 2050 Industrial Case reaches 100 GW in summer and 80 GW in winter. The 2050 all sectors scenario has the largest statewide electricity demand, with a peak power of nearly 170 GW in summer and 163 GW in winter.

Figure 94: Statewide Electricity Demand Comparison - Summer 2050

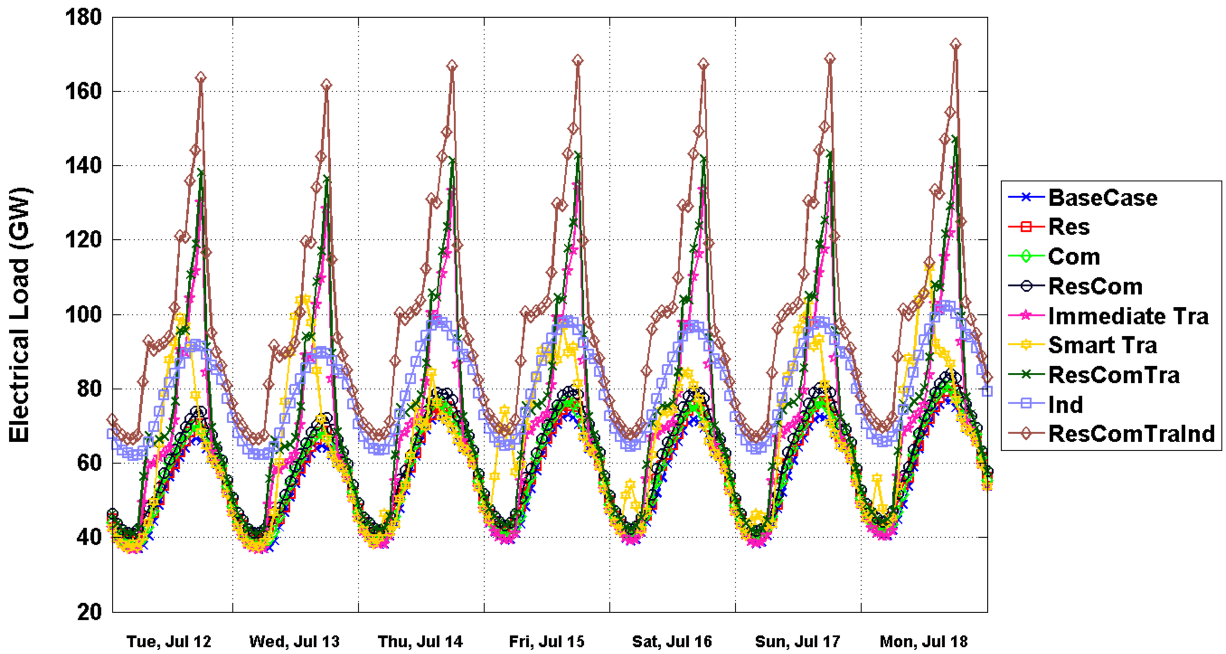
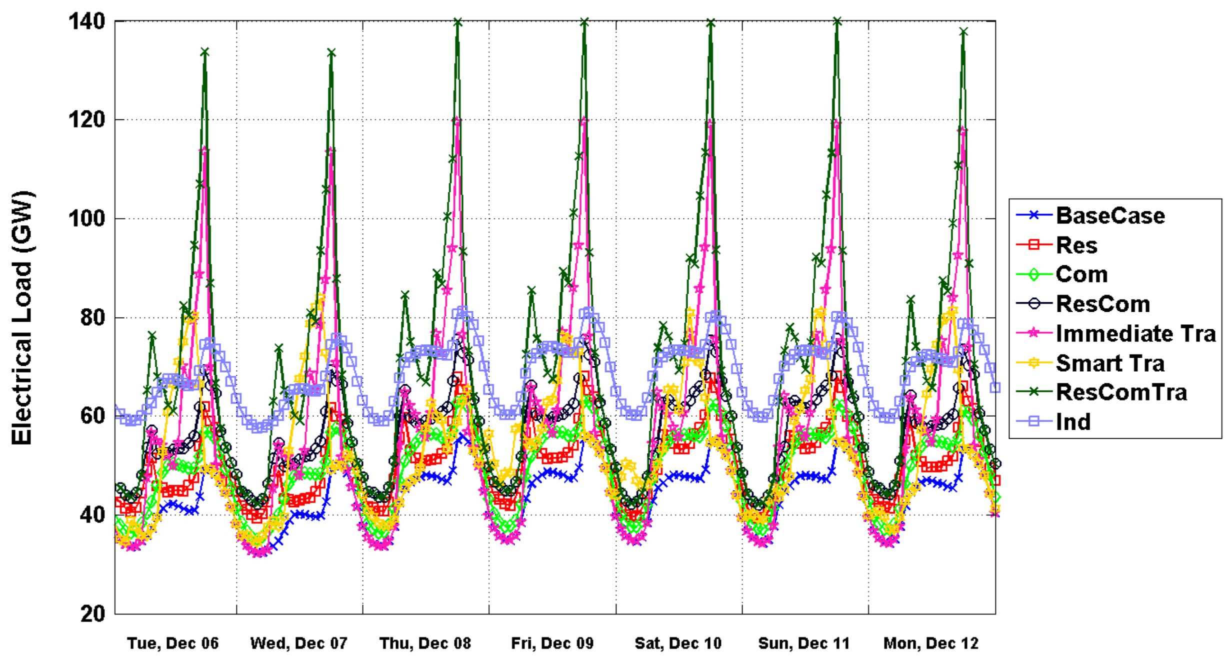


Figure 95: Statewide Electricity Demand Comparison - Winter 2050



4.2.3 Renewable Power

4.2.3.1 Renewable Power of 2020 Scenarios

Figure 96 and 97 compare the renewable power of 2020 scenarios in summer and winter. Since we assume 33% of statewide electricity demand is supplied by renewable energies in 2020, greater electricity demand results in higher amounts of installed renewable capacity. Therefore, installed capacity and power generation of renewable resources are proportional to the statewide electricity demand.

Figure 96: Renewable Power Comparison - Summer 2020

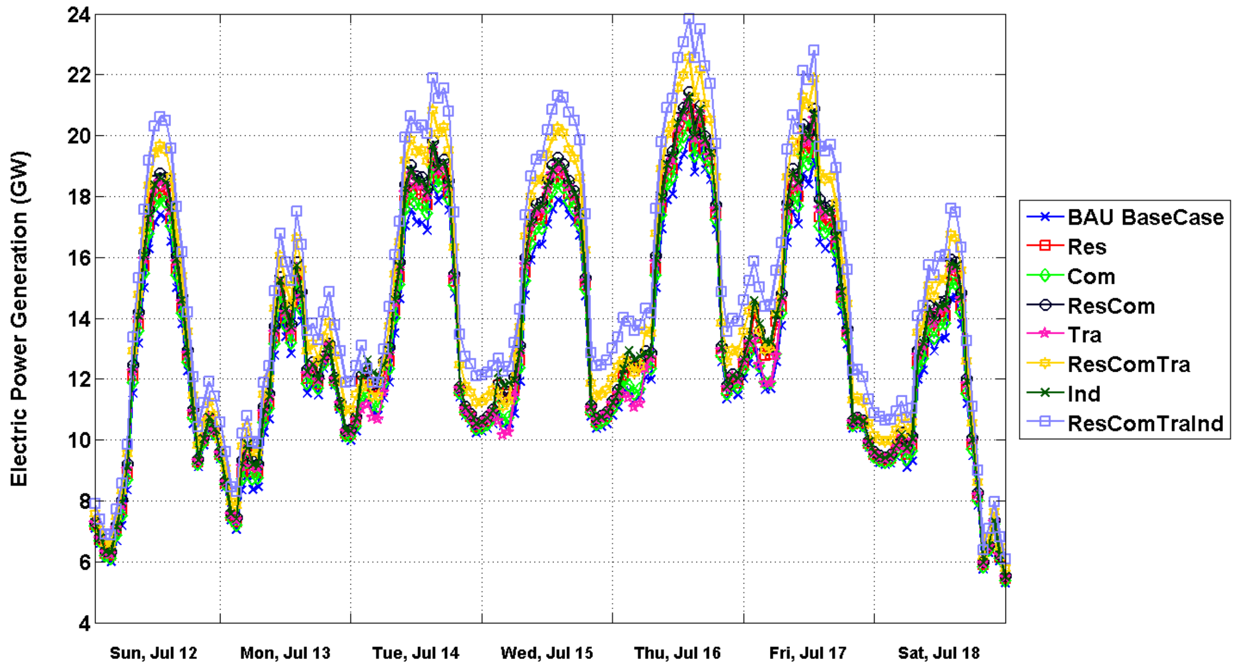
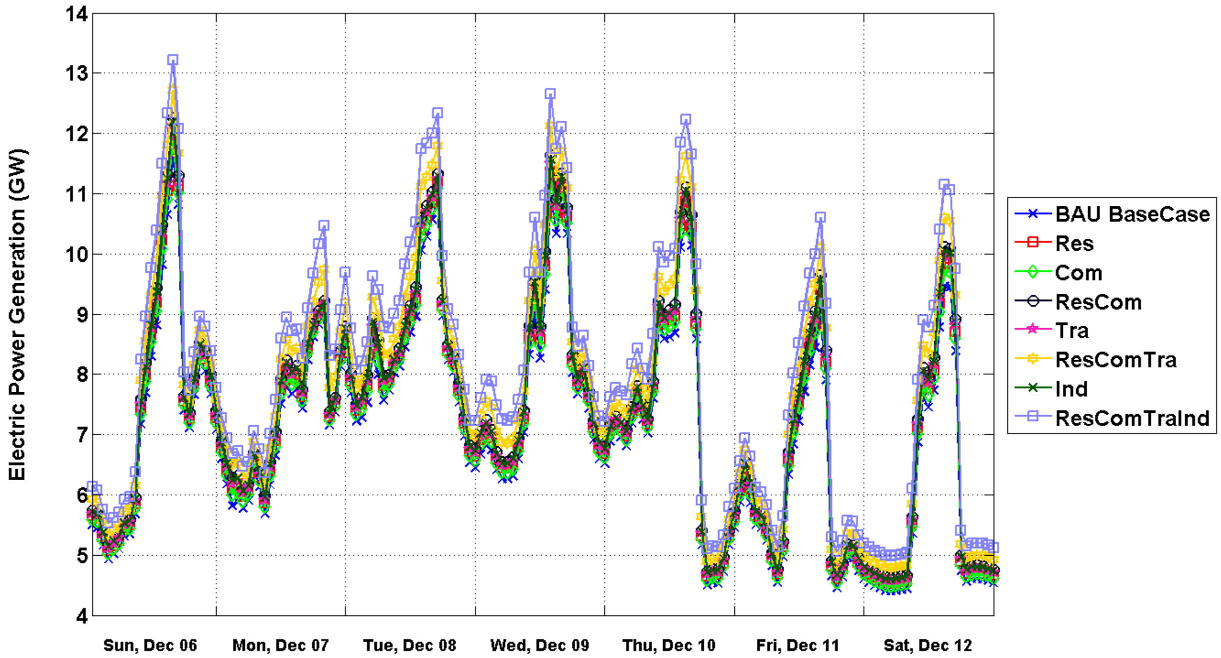


Figure 97: Renewable Power Comparison - Winter 2020



4.2.3.2 Renewable Power of 2030 Scenarios

Figure 98 and 99 compare the renewable power generation of 2030 scenarios in summer and winter; these results are based on 50% renewable penetration in 2030. The peak renewable power generation of Base Case is less than 40 GW in summer and nearly 20 GW in winter. Although statewide electricity demand of 2030 ResComTra case is higher than 2030 Ind case, their renewable load profiles are quite similar. This is mainly due to the fact that peak demand of 2030 ResComTra Case occurs in the evening, when solar power is not available; therefore, this scenario cannot absorb renewable power at times need, which results in less renewable power delivered to load.

Figure 98: Renewable Power Comparison - Summer 2030

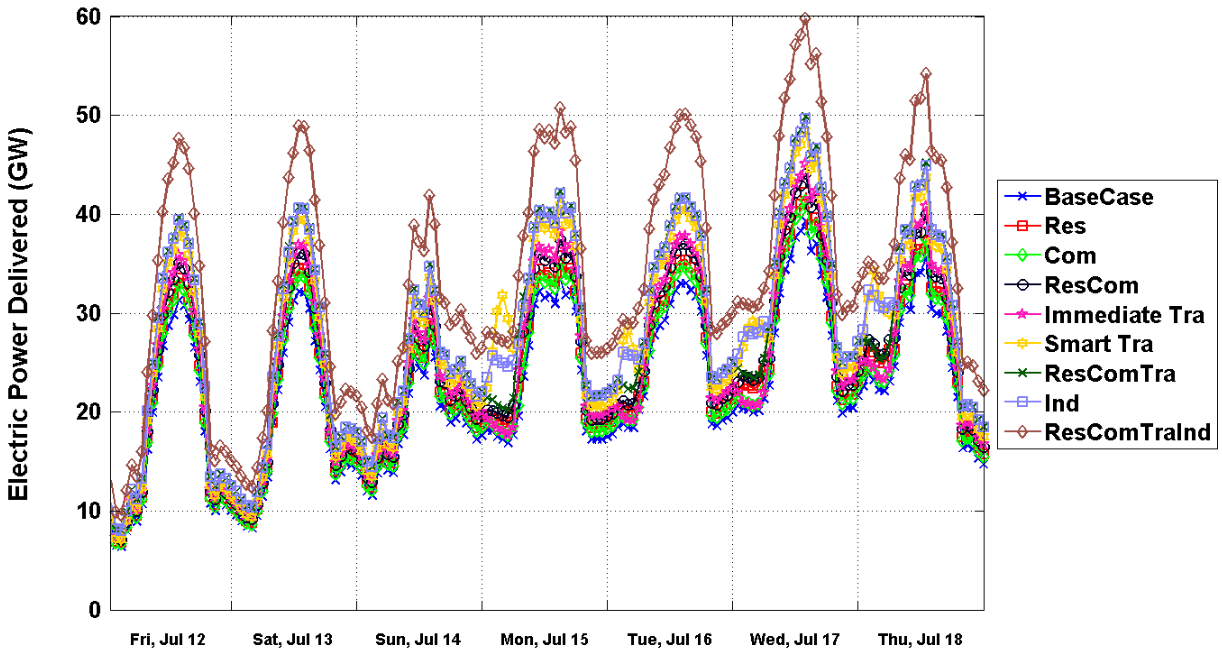
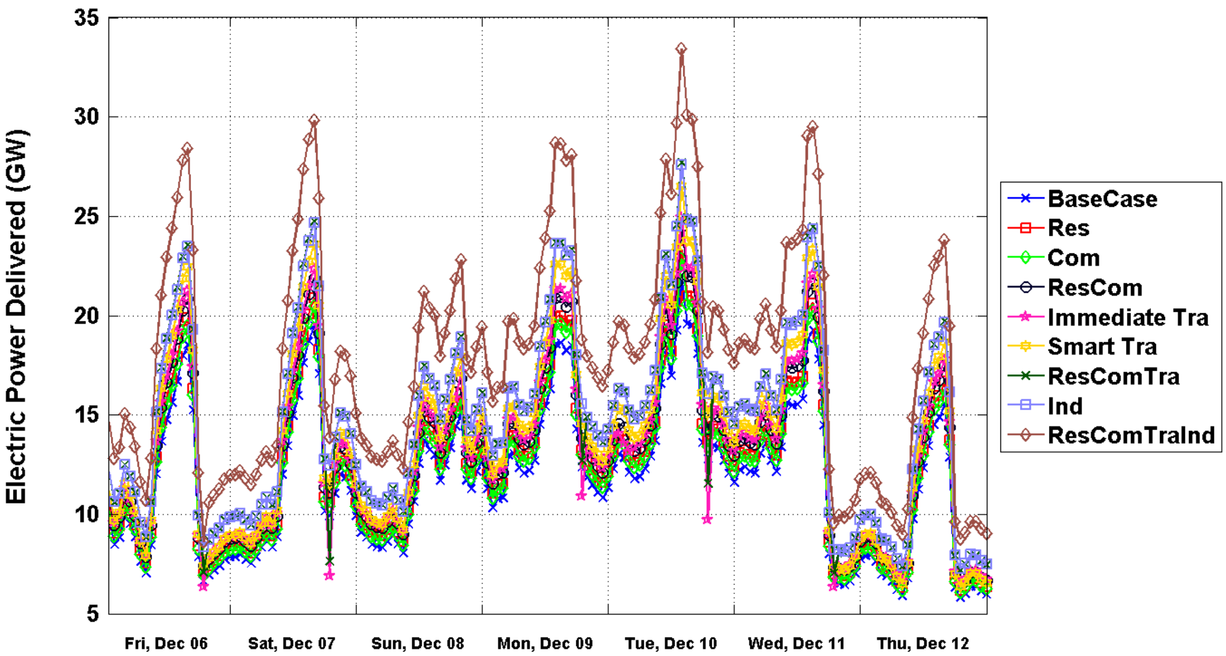


Figure 99: Renewable Power Comparison - Winter 2030



4.2.3.3 Renewable Power of 2050 Scenarios

Figure 100 and 101 compare the renewable power generation of 2050 scenarios in summer and winter; these results are based on 80% renewable penetration in 2050. The peak renewable power generation of Base Case is less than 75 GW in summer and nearly 45 GW in winter. Renewable power generation of 2050 all sectors case reach the peak of 163 GW in summer and 105 GW in winter.

Figure 100: Renewable Power Comparison - Summer 2050

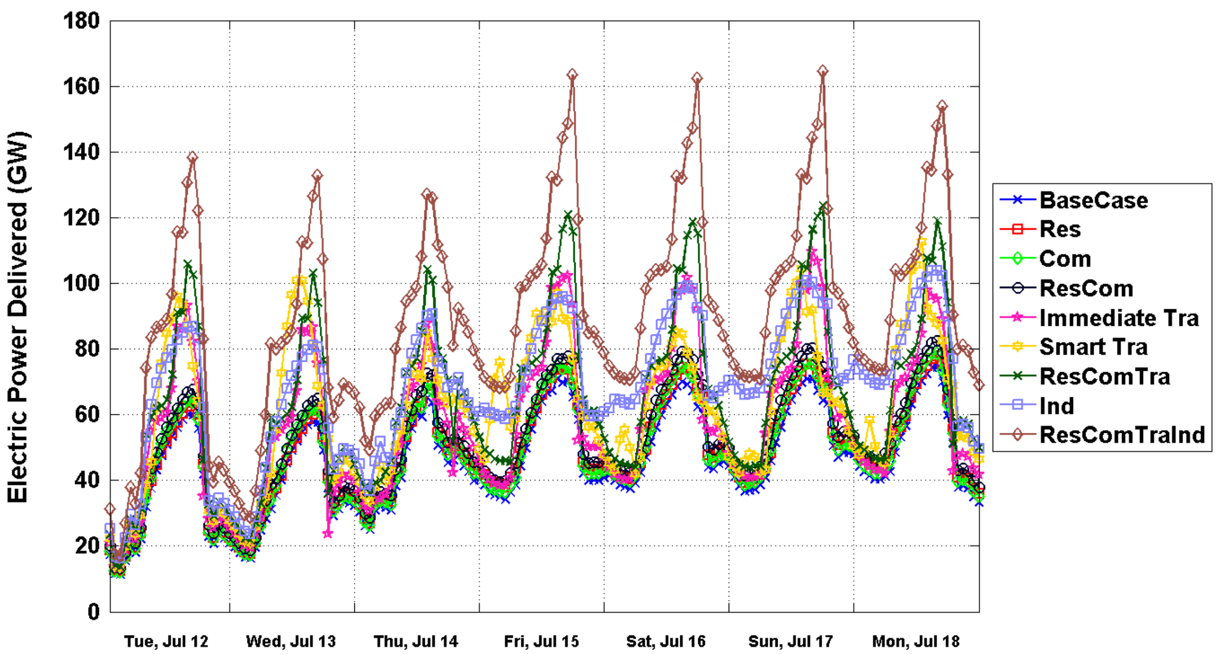
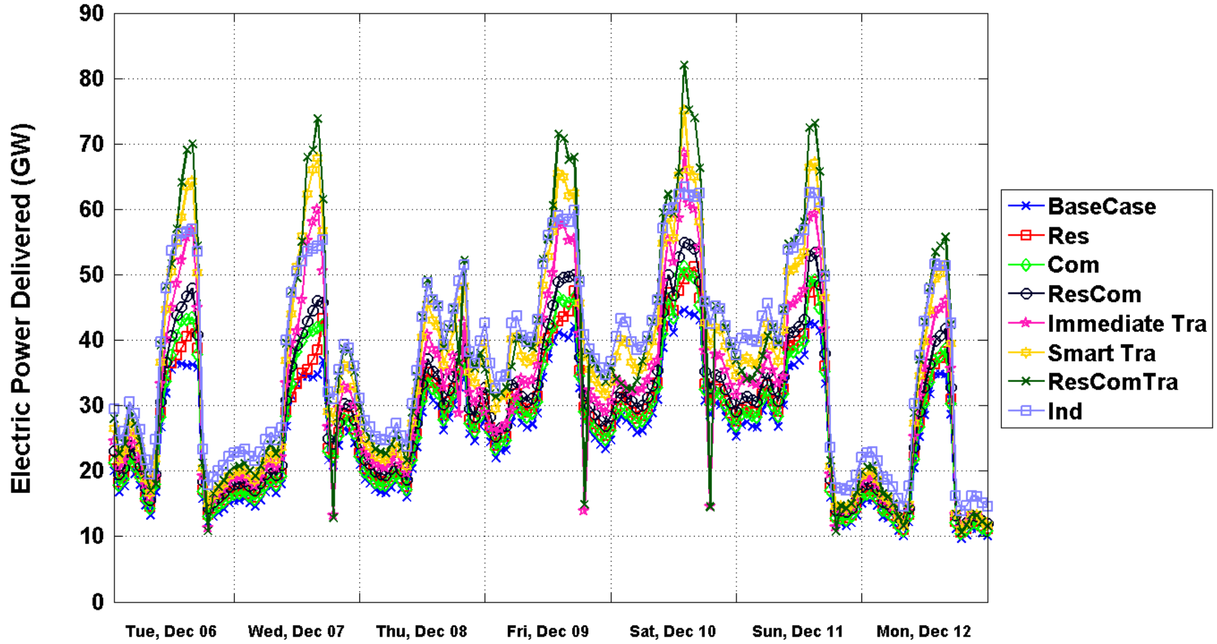


Figure 101: Renewable Power Comparison - Winter 2050



4.2.4 Renewable Power Curtailment

4.2.4.1 Renewable Power Curtailment of 2030 Scenarios

Figure 102 and 103 compare the renewable power curtailment of 2030 scenarios in summer and winter. Wind power is the main renewable resource curtailed due to early morning peak when there is not enough demand to use the excess power. Industrial and Buildings scenarios have the highest power curtailment exceeding 12 GW in summer, which is mainly due to nearly flat electrification demand that intensifies the existing grid dynamics. On the contrary, the Smart Transportation scenario has the lowest curtailment since all excess renewable power is used for smart charging of electric vehicles. Less renewable power is curtailed in winter since solar power generation is significantly lower. Moreover, no renewable power is curtailed in Smart Transportation during winter week, thanks to smart charging of electric vehicles, which maximizes charging when excess renewable power is available.

Figure 102: Renewable Power Curtailment Comparison - Summer 2030

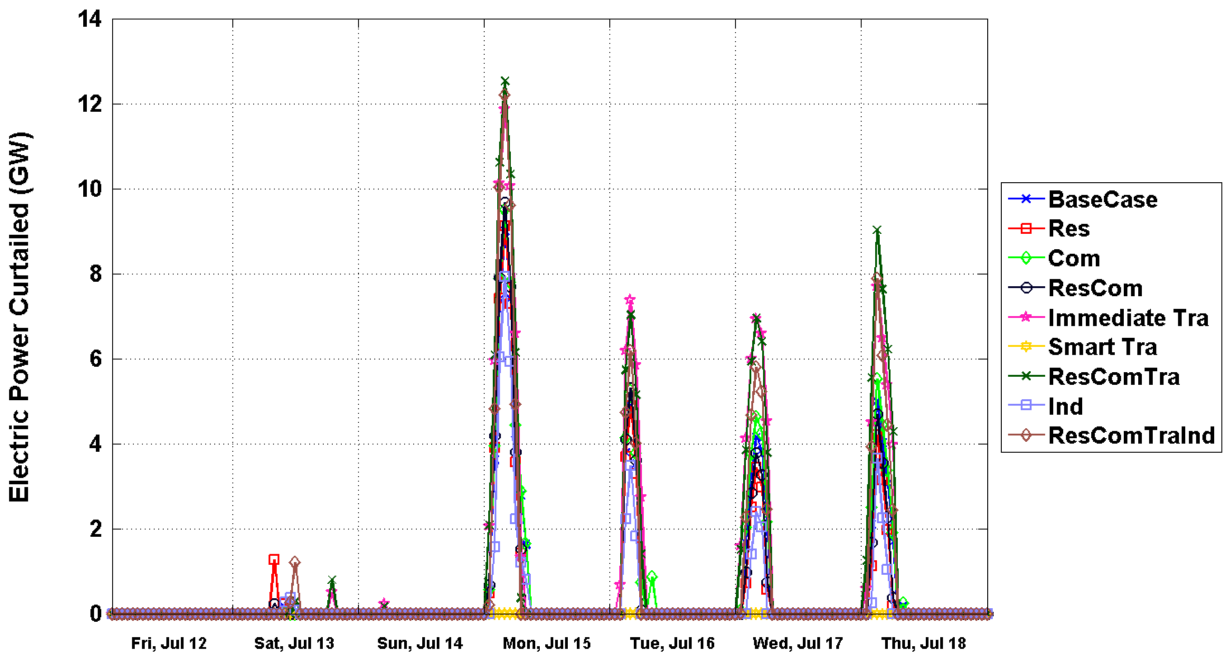
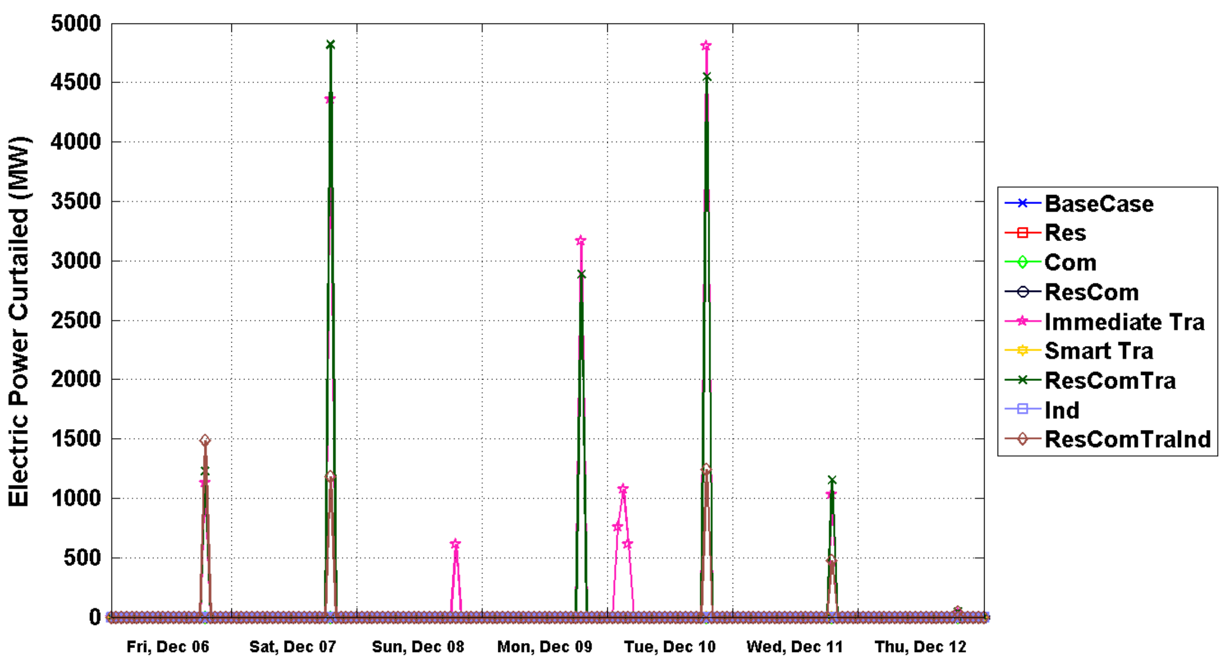


Figure 103: Renewable Power Curtailment Comparison - Winter 2030



4.2.4.2 Renewable Power Curtailment of 2050 Scenarios

Figure 104 and 105 compare the renewable power curtailment of 2050 scenarios in summer and winter. Comparing with 2030 results, significantly higher levels of renewable power is curtailed in 2050 due to higher electric penetration targets as well greater renewable penetration (80%), which results in more intermittency and additional dynamics to the statewide demand. Contrary to 2030 scenarios, the renewable power curtailment mostly occur in the evening in 2050, which is due to huge demand for immediate charging of electric vehicles. Similar to 2030 cases, the smart transportation scenario has the lowest power curtailment thanks to smart charging of electric vehicles, which maximizes charging when excess renewable power is available.

Figure 104: Renewable Power Curtailment Comparison - Summer 2050

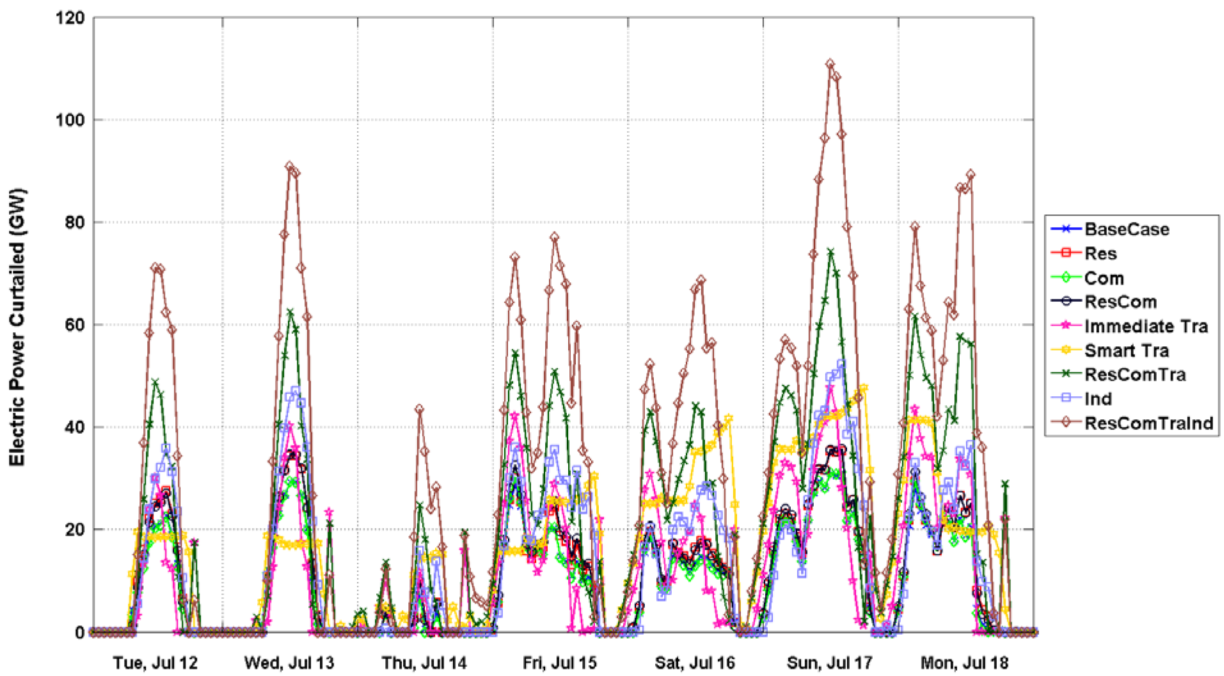
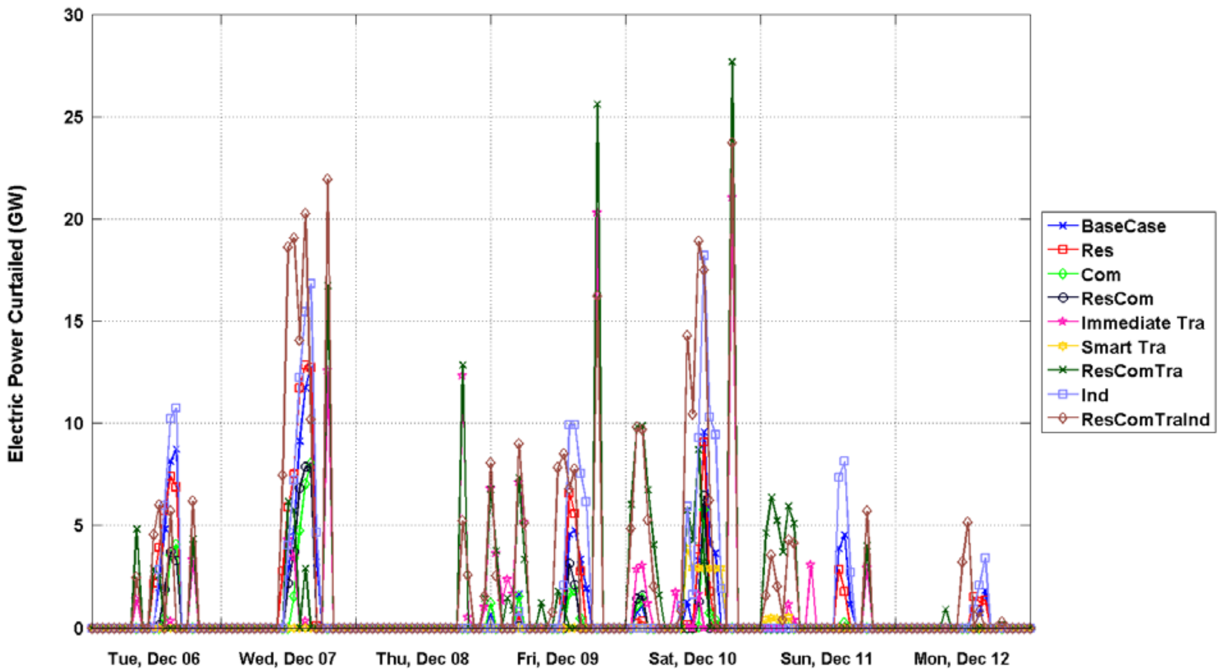


Figure 105: Renewable Power Curtailment Comparison - Winter 2050



4.2.5 Power Plants Electricity Generation

4.2.5.1 Power Plants Electricity Generation of 2020 Scenarios

Figure 106 and 107 display the hourly dispatch profile of power plants for 2020 scenarios in summer and winter. There is no significant change in power generation of summer week except a slight increase in the evening power generation on certain days for 2020 ResComTra and 2020 all sectors Cases. However, the power plants generation increases significantly in winter, due to larger residential and commercial heating demand as well as less availability of renewable resources.

Figure 106: Power Plants Electricity Generation Comparison - Summer 2020

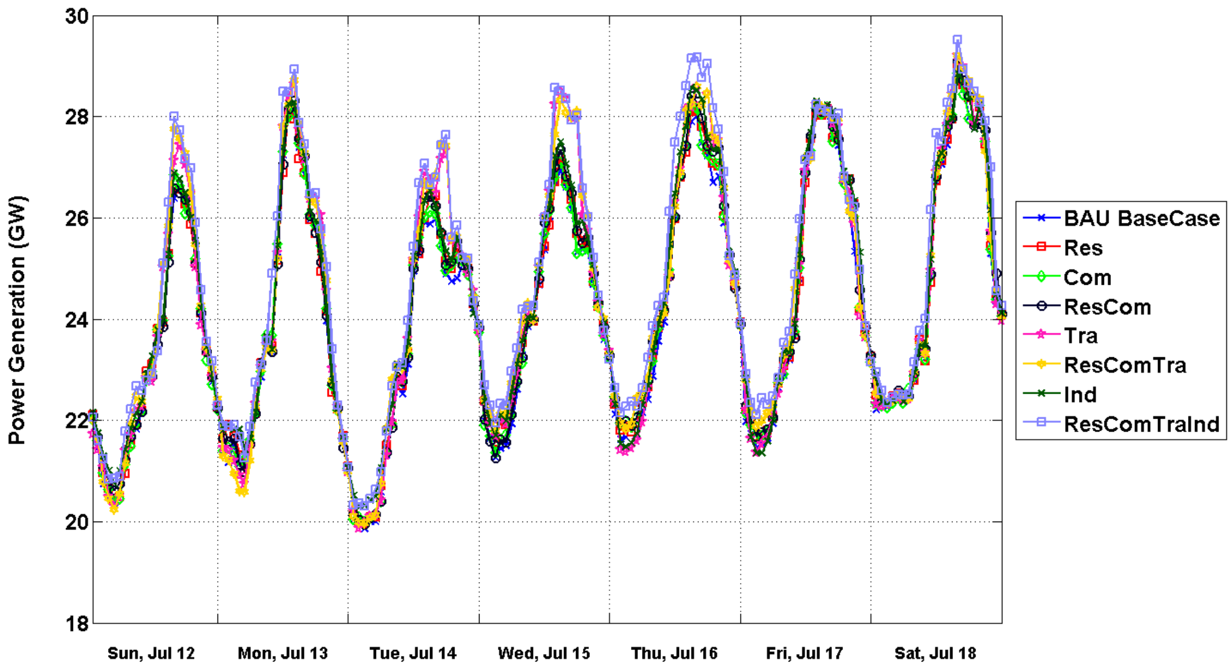
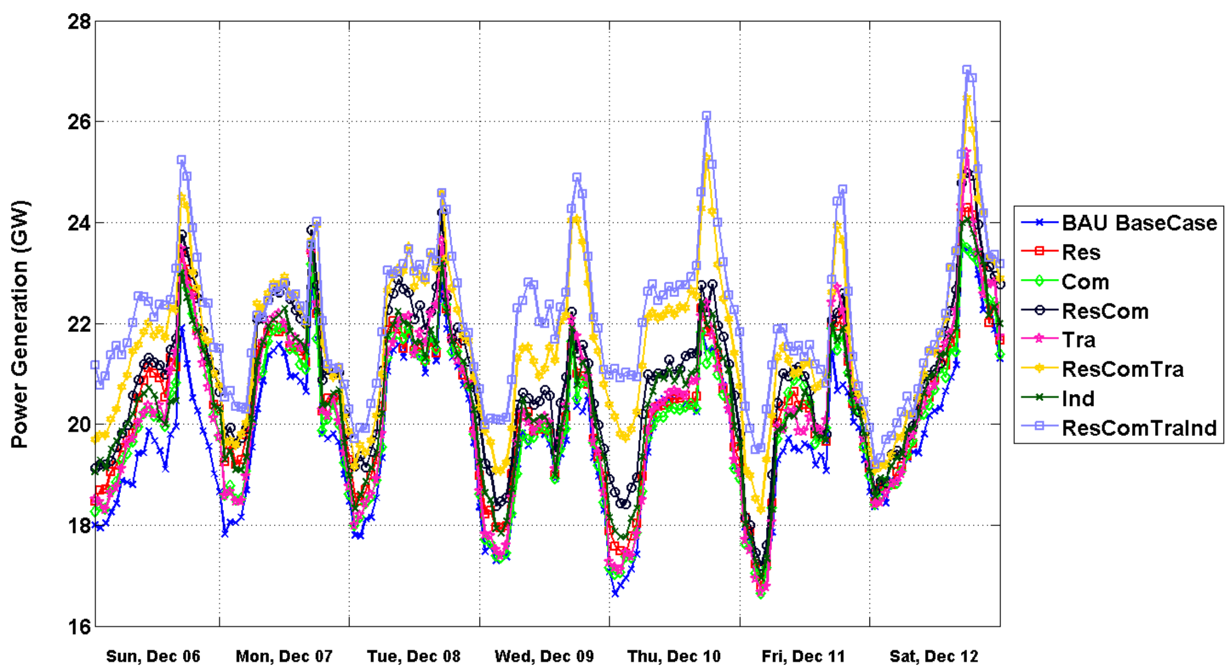


Figure 107: Power Plants Electricity Generation Comparison - Winter 2020



4.2.5.2 Power Plants Electricity Generation of 2030 Scenarios

Figure 108 and 109 show the hourly dispatch profile of power plants for 2030 scenarios in summer and winter. The power generation of electrification scenarios increases substantially as they demand greater electricity due to electrification. As would be expected, 2030 all sectors case has the largest increase in power plants electricity generation. Compared to summer, there are more spikes in winter power generation, which is primarily due to lower availability of renewable resources at peak demand hours. The power plants generation is maximized around evening for all scenarios due to peak power demand and minimum renewable power generation. Moreover, power plants generate minimum power around noon due to high solar power generation; however, the smart transportation scenario require higher generation of power plants in midday caused by high demand of smart EV charging that is maximized due to lower price of electricity during off-peak period. Therefore, smart transportation scenario result in lower dynamics, such as ramping and startup, and enhanced operation of power plants.

Figure 108: Power Plants Electricity Generation Comparison - Summer 2030

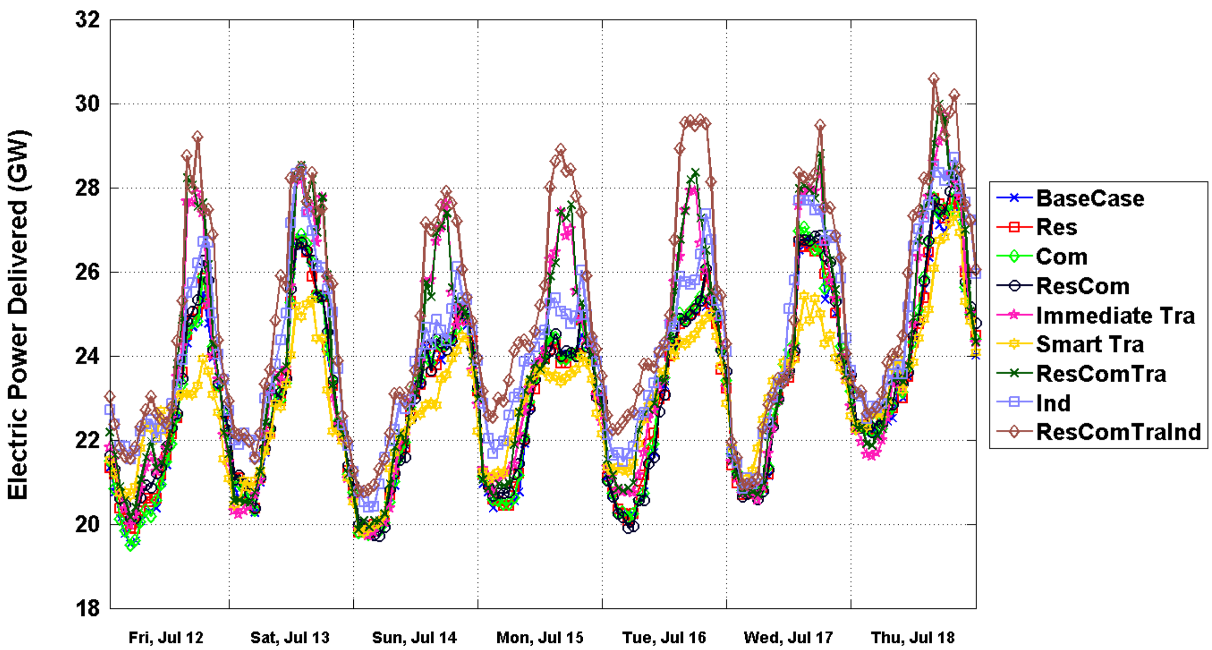
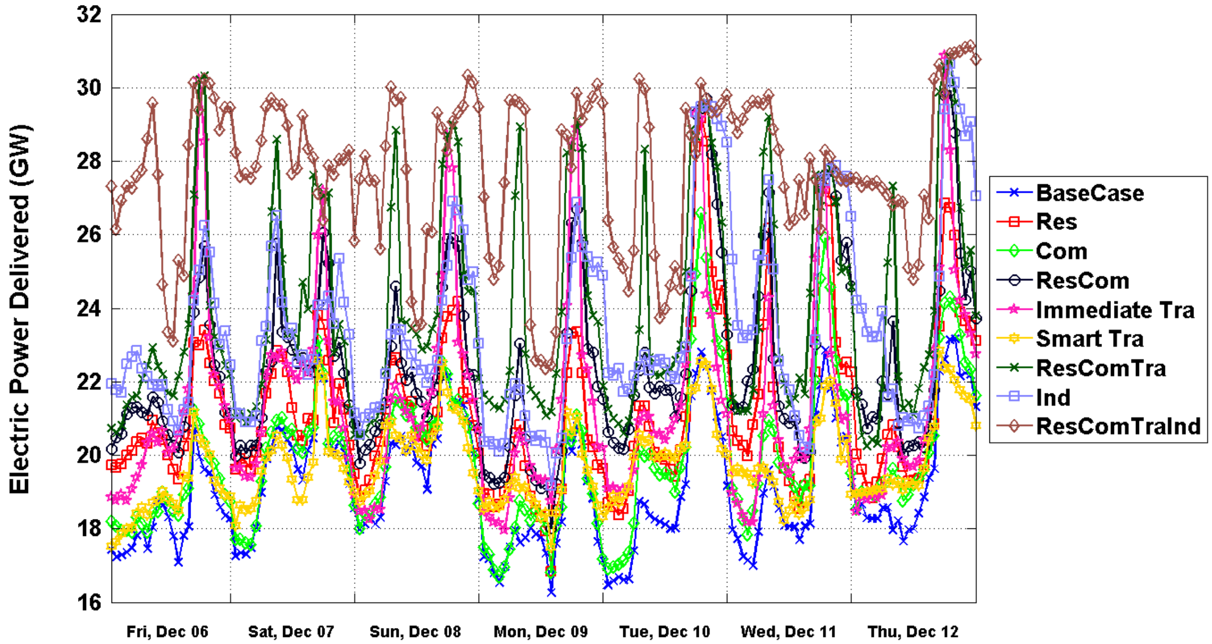


Figure 109: Power Plants Electricity Generation Comparison - Winter 2030



4.2.5.3 Power Plants Electricity Generation of 2050 Scenarios

Figure 110 and 111 display the hourly dispatch profile of power plants for 2050 scenarios in summer and winter. Similar to 2030 results, the power generation of electrification scenarios increases substantially as they have larger electricity demand due to electrification. Interestingly, the 2050 immediate transportation case has the highest peak power generation, which is expected to be lower than that of all sectors scenario. This can be interpreted as the excess peak power of all sector scenarios are met by imports from out-of-state resources. Buildings and industrial scenarios have the highest ramping rates (worst dynamics), while smart Transportation have the smoothest power plants operation.

Figure 110: Power Plants Electricity Generation Comparison - Summer 2050

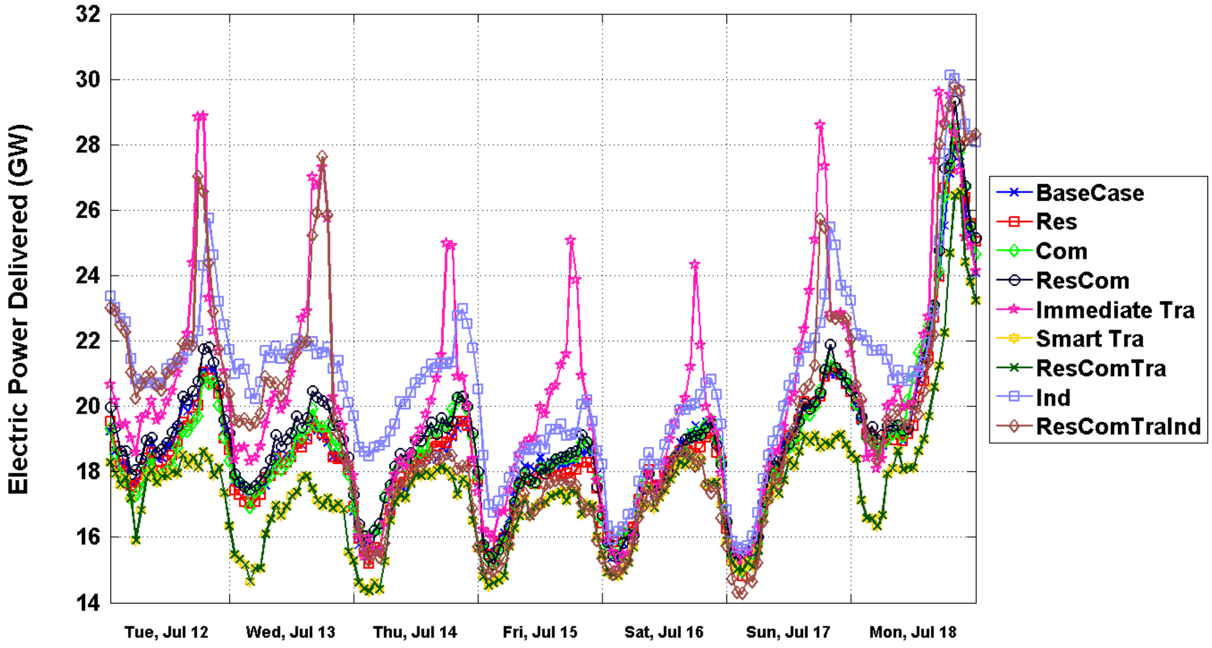
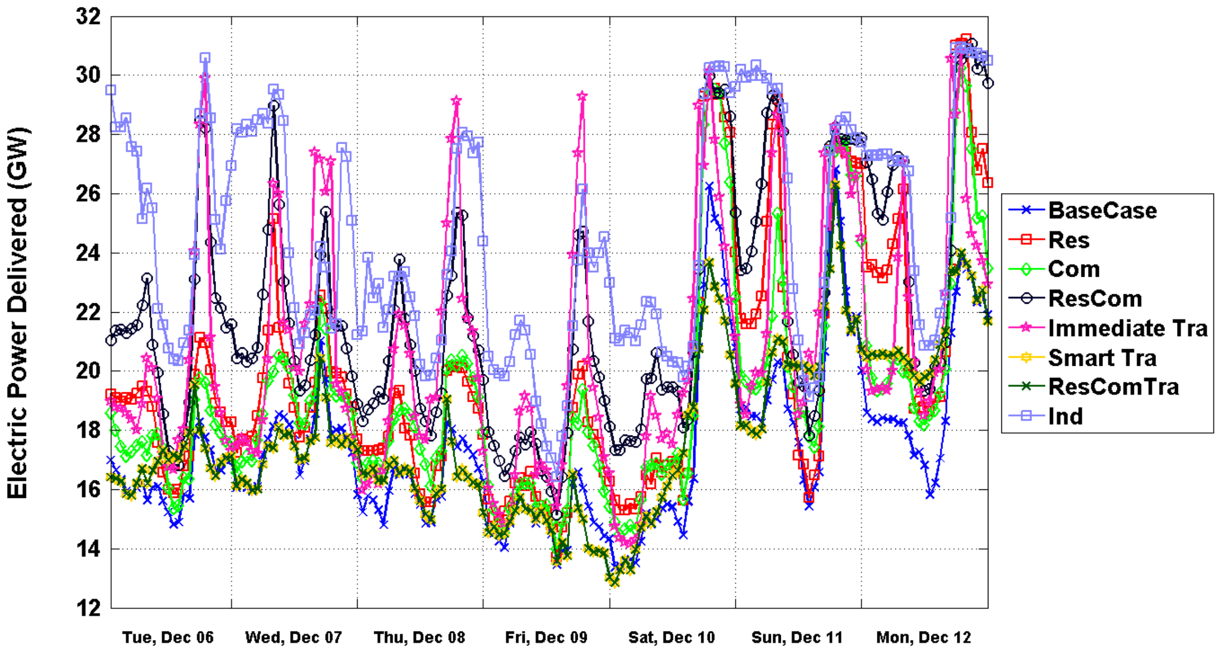


Figure 111: Power Plants Electricity Generation Comparison - Winter 2050



4.2.6 Net Power Imports

4.2.6.1 Net Power Imports of 2030

Scenarios compare the net power imports of 2030 scenarios in summer and winter. The Smart Transportation scenario balances the load with minimum power imports from out-of-state resources thanks to high flexibility of EV smart charging. Contrary, other electrification scenarios need power imports as high as 27 GW in order to balance the grid; the majority of power imports occur during evening peak, when renewable power generation is not sufficient. The All Sectors scenario has the maximum net power imports due to huge electrification demand and shortage of in-state power resources. Electrification scenarios need higher power imports (up to 42 GW) in winter for balancing the load due to higher electrification demand and less availability of solar power generation.

Figures 112-113 compare the net power imports of 2030 scenarios in summer and winter. The Smart Transportation scenario balances the load with minimum power imports from out-of-state resources thanks to high flexibility of EV smart charging. Contrary, other electrification scenarios need power imports as high as 27 GW in order to balance the grid; the majority of power imports occur during evening peak, when renewable power generation is not sufficient. The All Sectors scenario has the maximum net power imports due to huge electrification demand and shortage of in-state power resources. Electrification scenarios need higher power imports (up to 42 GW) in winter for balancing the load due to higher electrification demand and less availability of solar power generation.

Figure 112: Net Power Imports Comparison - Summer 2030

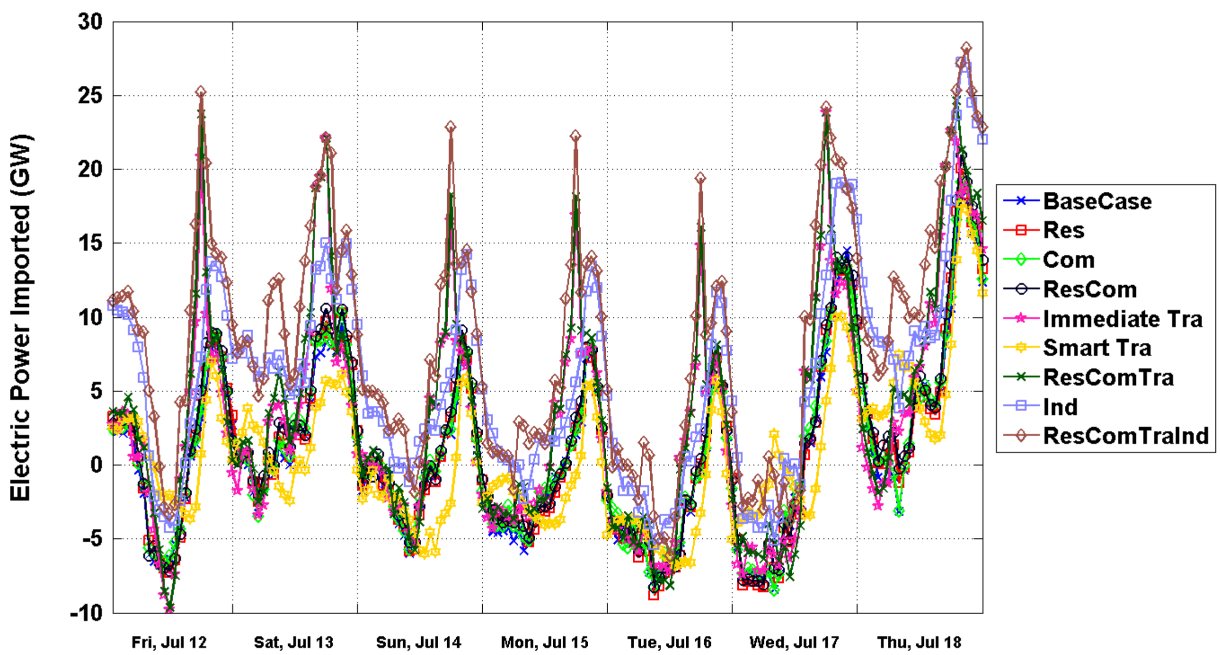
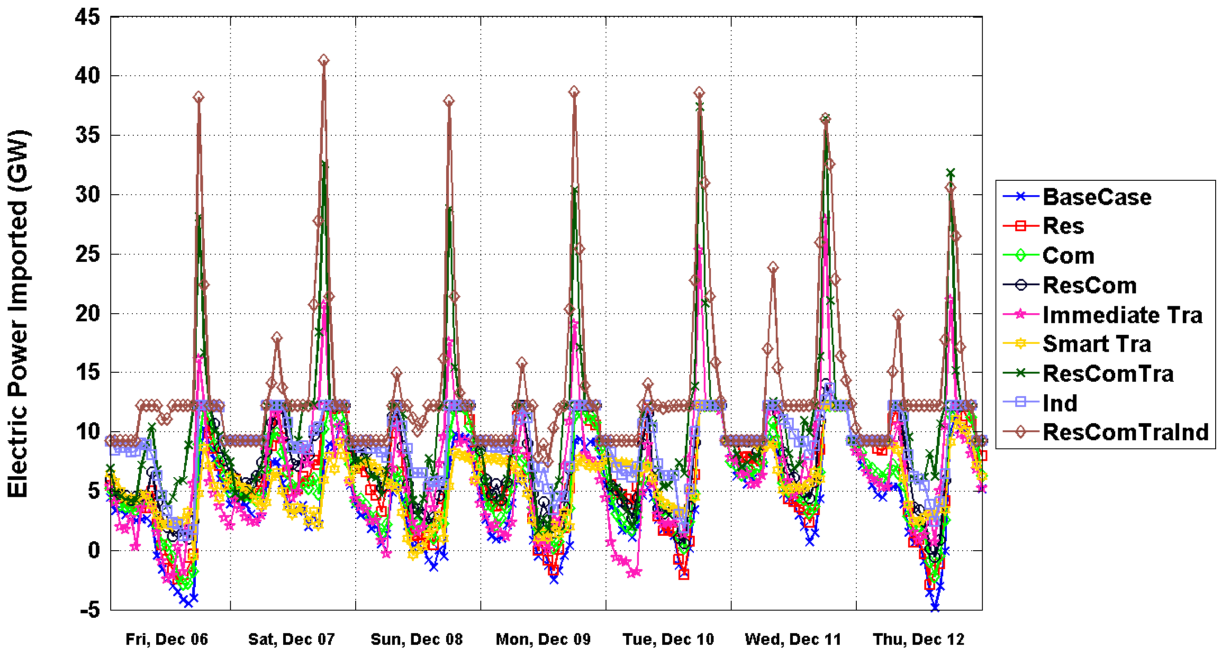


Figure 113: Net Power Imports Comparison - Winter 2030



4.2.6.2 Net Power Imports of 2050 Scenarios

Figure 114and 115 compare the net power imports of 2050 scenarios in summer and winter. The Smart Transportation scenario balances the load with minimum power imports from out-of-state resources thanks to high flexibility of EV smart charging. Contrary, other electrification scenarios require power imports as high as 30 GW to balance the grid; the majority of power imports occur during evening peak, when renewable power generation is not sufficient. The All Sectors scenario has the maximum net power imports due to huge electrification demand and shortage of in-state power resources. Electrification scenarios need higher power imports (up to 42 GW) in winter for balancing the load due to higher electrification demand and less availability of solar power generation.

Figure 114: Net Power Imports Comparison - Summer 2050

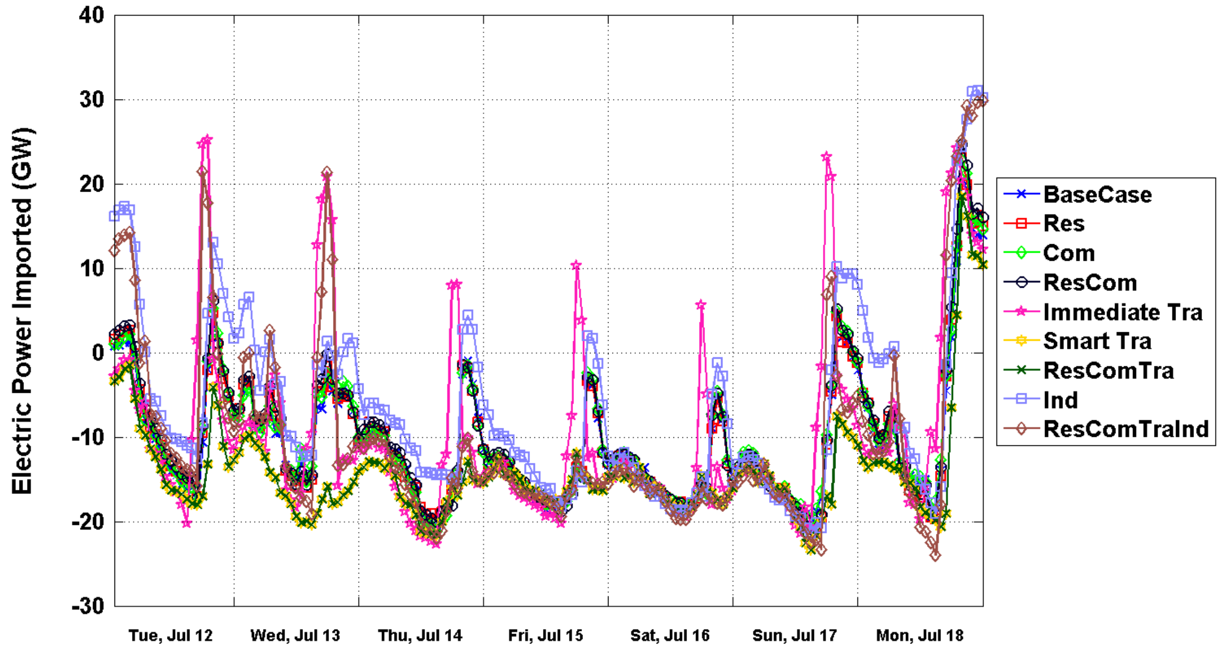
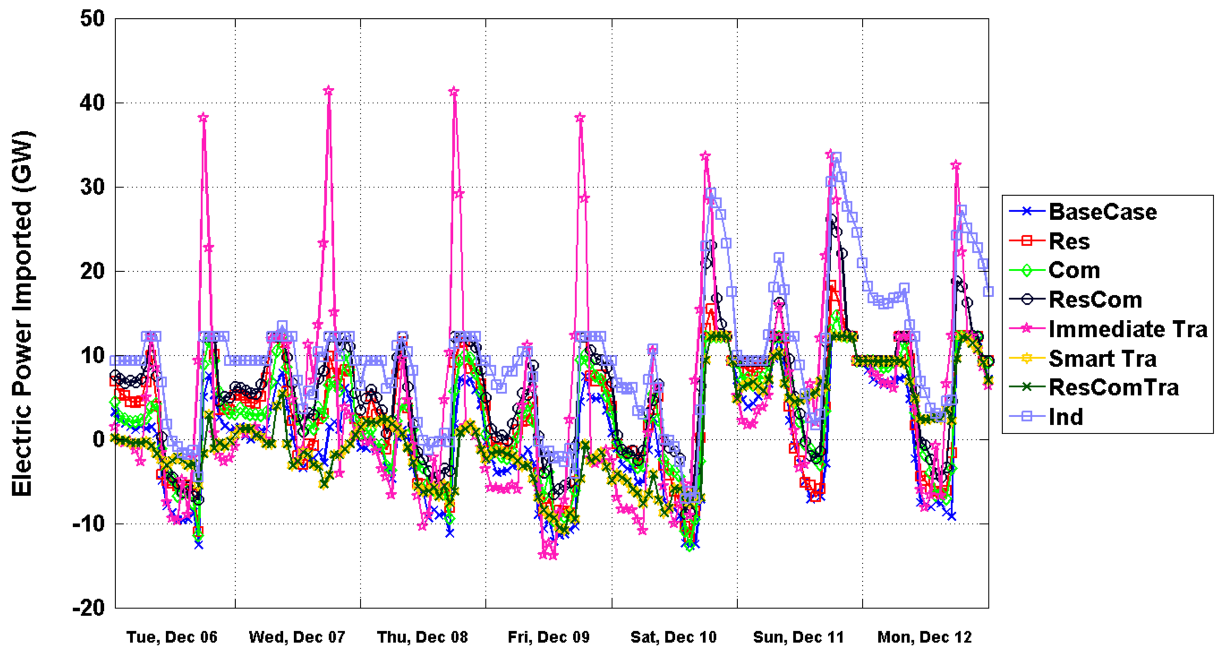


Figure 115: Net Power Imports Comparison - Winter 2050



4.3 Emissions Impacts

4.3.1 Criteria Pollutant Emissions

4.3.1.1 Power Plants NOx Emissions of 2020 Scenarios

Figure 116 and Figure 117 display the NOx emissions from power plants for 2020 scenarios in summer and winter. During peak hours, when demand increase substantially, peaking plants start operating and causes increased NOx emission, which is primarily due to dynamic (startup and ramping) emissions that results from sudden changes in power plants operation. As would be expected, scenarios with largest peak demand, such as 2020 all sectors electrification case, yield highest increases in NOx emissions.

Figure 116: Power Plants NOx Emission Comparison - Summer 2020

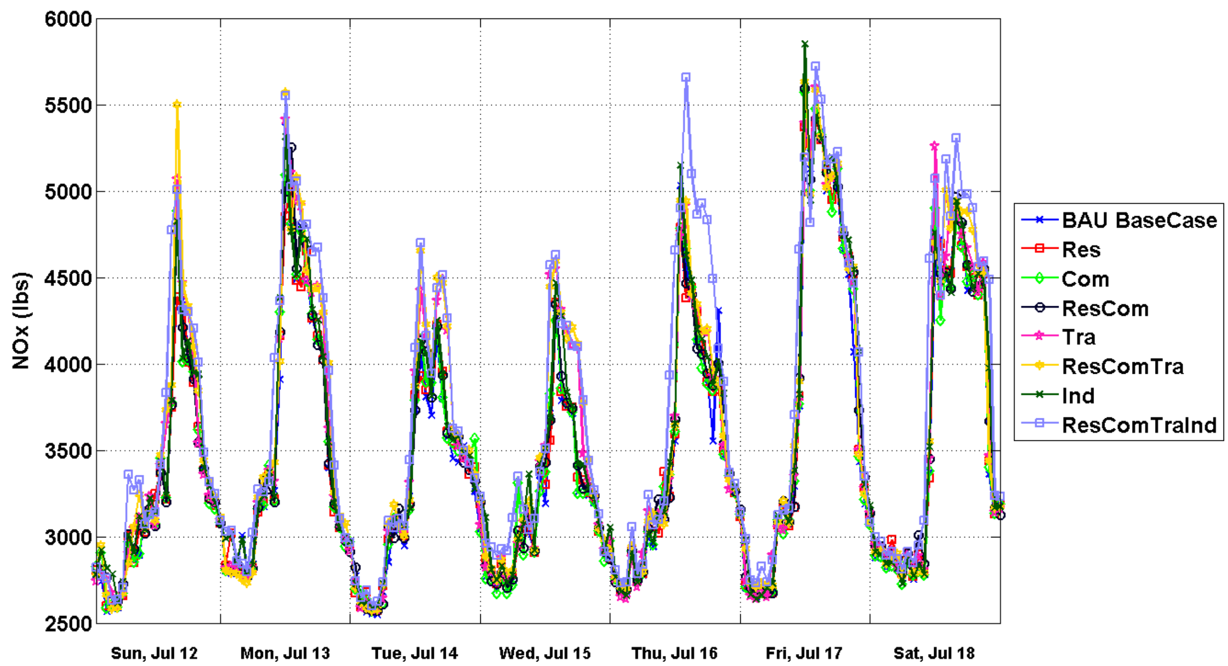
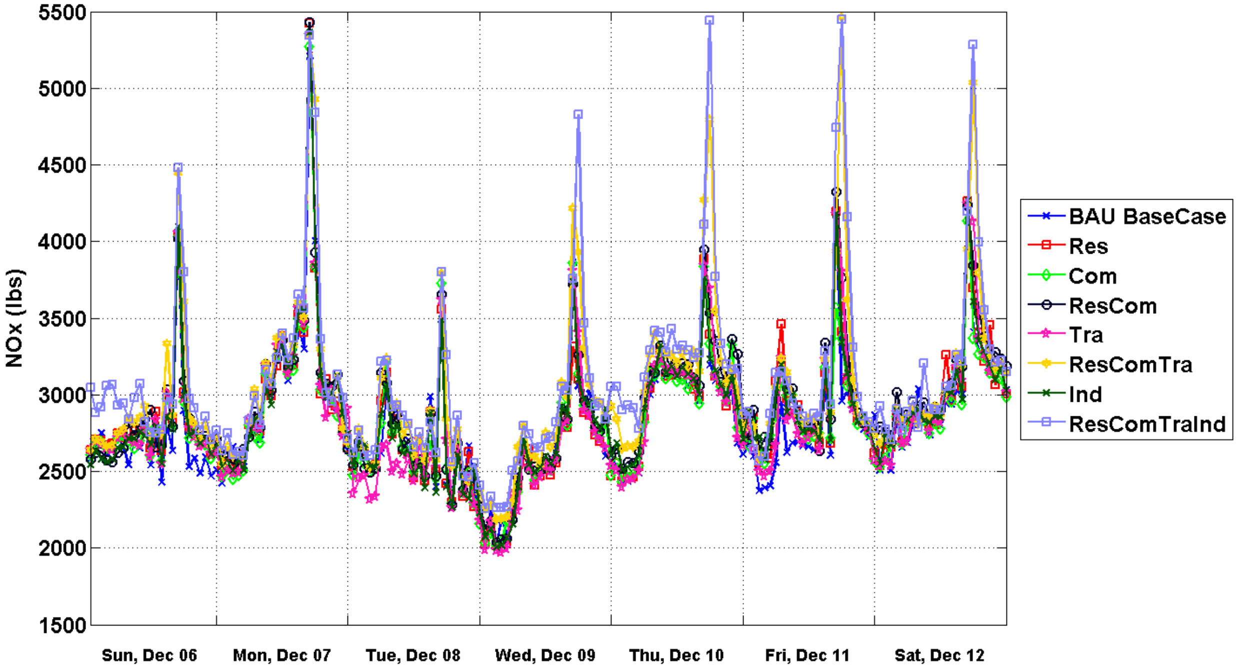


Figure 117: Power Plants NOx Emission Comparison - Winter 2020



4.3.1.1 Power Plants NOx Emissions of 2030 Scenarios

Figure 118 and 119 show the NOx emissions from power plants for 2030 scenarios in summer and winter. During demand peak hours, NOx emissions increase substantially due to dynamic emissions from peaking power plants. For example, the total NOx emissions from power plants (≈7000 lbs.) in 2030 all sectors case is nearly double as NOx emissions (≈3500) in 2030 Base Case. The increase in NOx emissions of electrification scenarios in winter is higher compared to summer due to less availability of renewable resources. The dynamic emissions originate from dynamic operation of each plant, which results in startup and ramping emissions. The Smart Transportation scenario has the lowest dynamic emission peak owing to high flexibility of smart charging strategy in balancing the load based on availability of resources, resulting in smaller dynamics and smoother operation of power plants.

Figure 118: Power Plants NOx Emission Comparison - Summer 2030

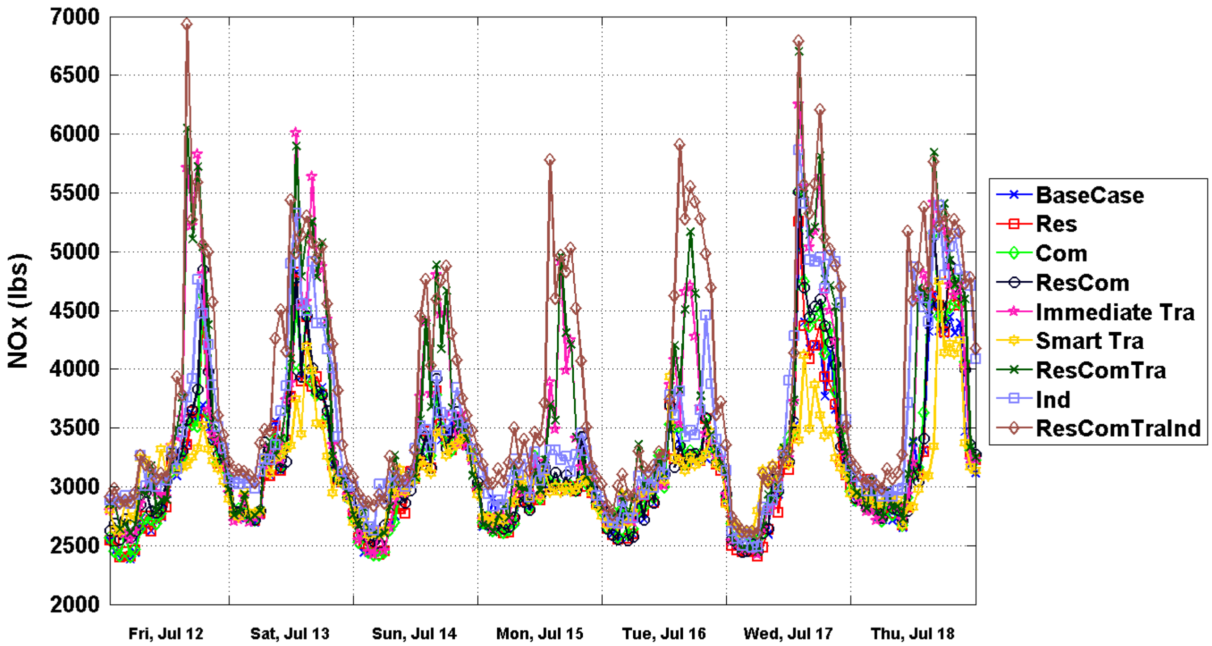
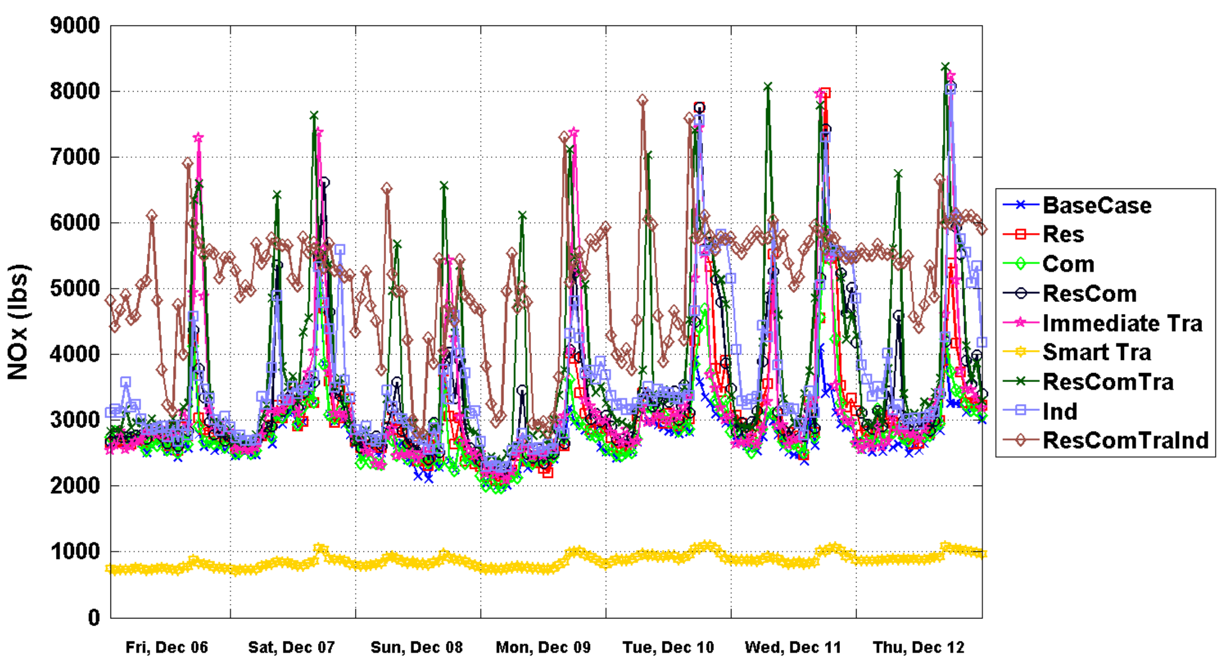


Figure 119: Power Plants NOx Emission Comparison - Winter 2030



4.3.1.2 Power Plants NOx Emissions of 2050 Scenarios

Figure 120 and 121 show the NOx emissions from power plants for 2050 scenarios in summer and winter. The immediate transportation scenario generates the maximum NOx emissions, primarily huge evening peak for immediate charging of electric vehicles as well as inferior dynamics.

Figure 120: Power Plants NOx Emission Comparison - Summer 2050

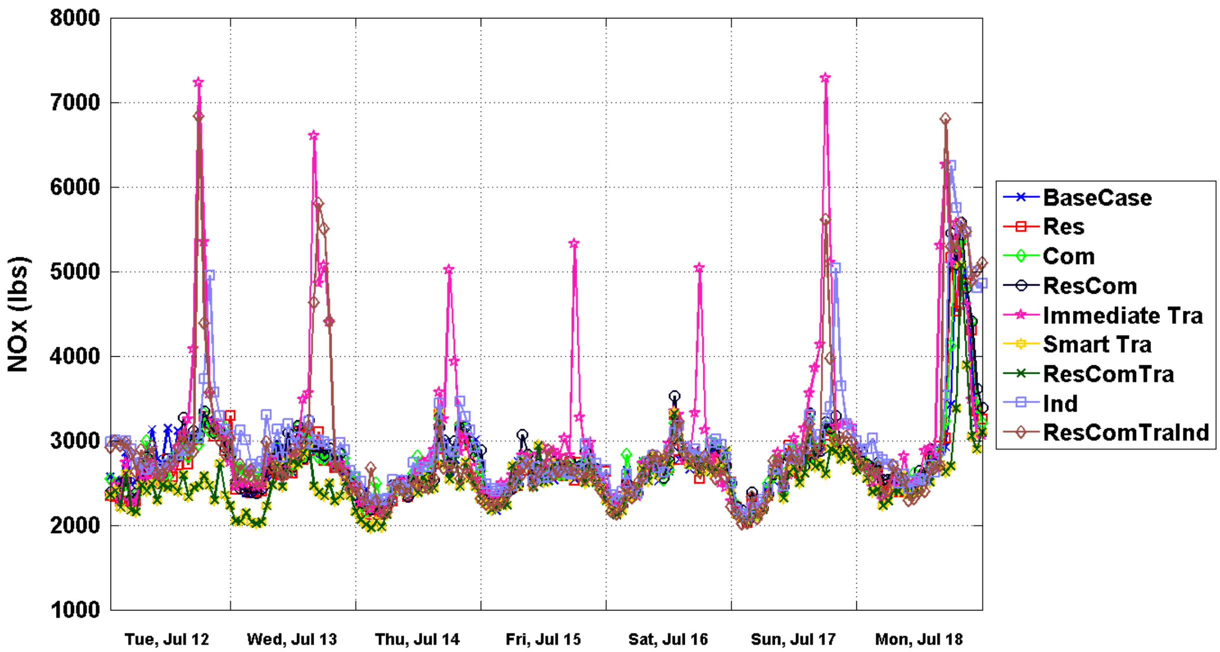
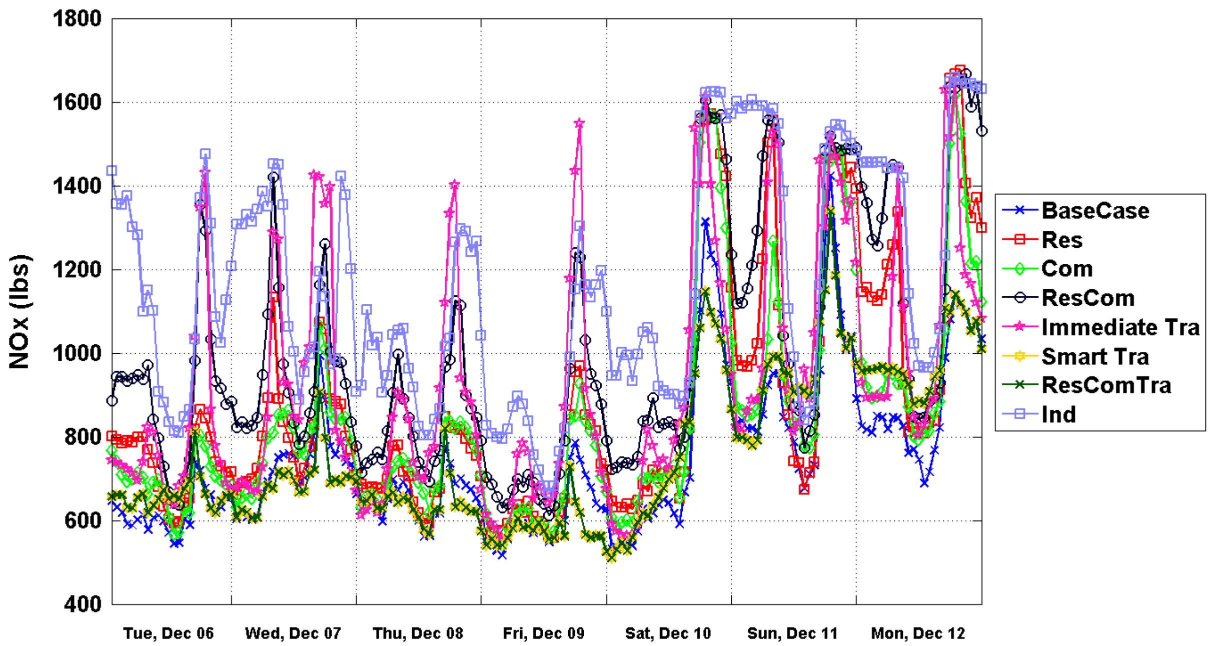


Figure 121: Power Plants NOx Emission Comparison - Winter 2050



4.3.2 Greenhouse Gas Emissions

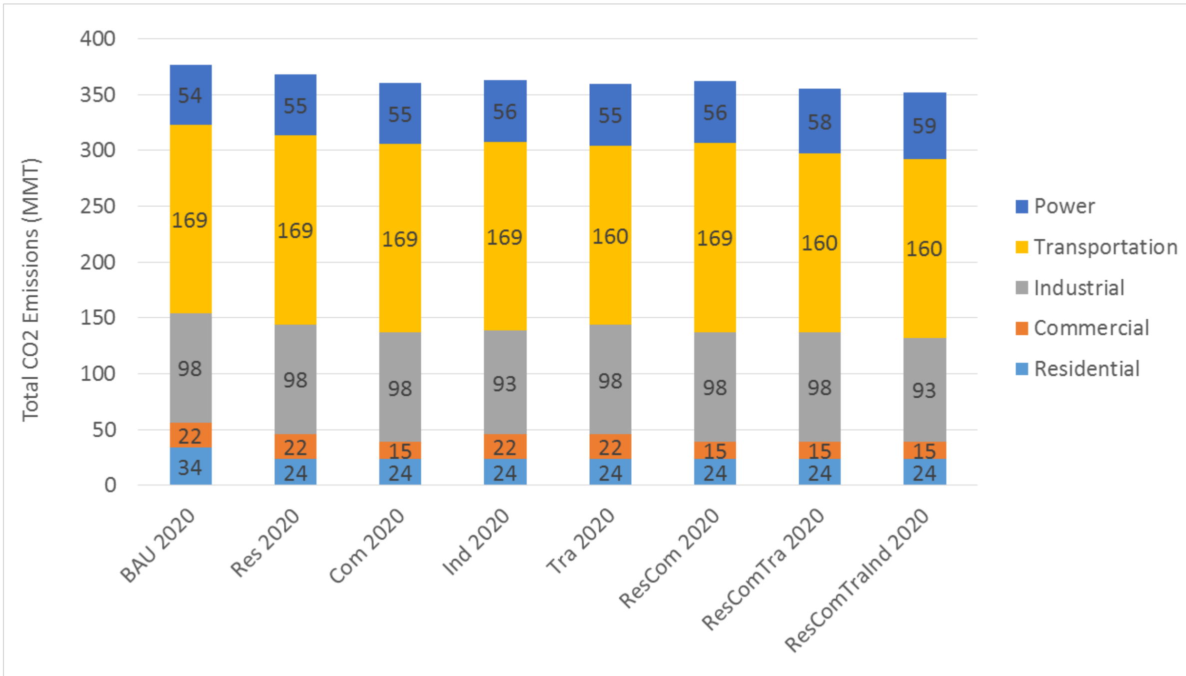
4.3.2.1 GHG Emissions of 2020 Scenarios

Table 10 displays the resulting impacts on CO_2 emissions for the 2020 scenarios relative to the Base Case. As can be seen in Figure 122, all 2020 cases result in GHG emission reductions relative to the no electrification case (Base Case) as the total CO_2 emission reductions of end-use sectors is greater than the power sector emission increases. The largest CO_2 emission reduction occurs in the All Sectors Electrification scenario (2020 ResComTraInd Case) at nearly -9.5%, followed by 2020 ResComTra Case, which yields a total CO_2 emission decrease of 7.9%. However, the smallest CO_2 emission saving occurs in the Residential Electrification scenario (2020 Res Case) with 3.1% decrease compared to the Base Case.

Table 10: CO2 Emission Reductions after Electrification for 2020 Cases

CA CO2 Emissions Reductions After Electrification (MMTCO2) 2020 Cases								
Cases	**BAU 2020**	**Res 2020**	**Com 2020**	**Ind 2020**	**Tra 2020**	**ResCom 2020**	**ResComTra 2020**	**ResComTraInd 2020**
Residential	34	**24**	24	24	24	**24**	**24**	**24**
Commercial	22	22	**15**	22	22	**15**	**15**	**15**
Industrial	98	98	98	**93**	98	98	98	**93**
Transportation	169	169	169	169	**160**	169	**160**	**160**
Power	54	55	55	56	55	56	58	59
Total (MMTCO2)	377	368	361	363	360	362	355	352
% Change	0.0%	-2.4%	-4.3%	-3.6%	-4.6%	-3.9%	-5.7%	-6.6%

Figure 122: Total CO_2 Emissions for 2020 Electrification Scenarios



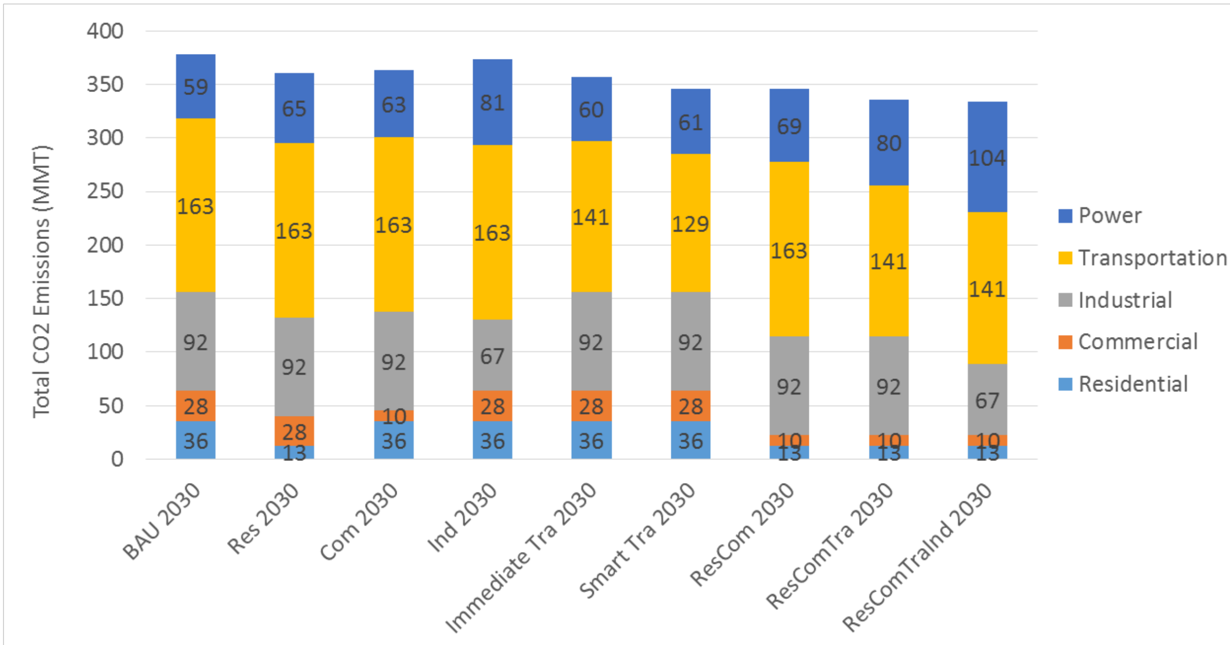
GHG Emissions of 2030 Scenarios

Table 11 displays the resulting impacts on CO_2 for the 2030 scenarios relative to the Baseline. As can be seen in Figure 123, similar trends emerge relative to the 2020 cases. All individual scenarios yield significant reductions in GHG emissions with the All Sectors Electrification Scenario (2030 ResComTraInd Case) yielding the highest decrease (nearly 31%). The next largest CO_2 emission savers are 2030 ResComTra and 2030 ResCom Cases with achieving 23% and 12.9% net reductions in GHG emissions, respectively.

Table 11: CO2 Emission Reductions After Electrification for 2030 Cases

CA CO2 Emissions Reductions After Electrification (MMTCO2) 2030 Cases									
Cases	**BAU 2030**	**Res 2030**	**Com 2030**	**Ind 2030**	**Immediate Tra 2030**	**Smart Tra 2030**	**ResCom 2030**	**ResComTra 2030**	**ResComTraInd 2030**
Residential	36	**13**	36	36	36	36	**13**	**13**	**13**
Commercial	28	28	**10**	28	28	28	**10**	**10**	**10**
Industrial	92	92	92	**67**	92	92	92	92	**67**
Transportation	163	163	163	163	**141**	**129**	163	**141**	**141**
Power	59	65	63	81	60	61	69	80	104
Total (MMTCO2)	378	360	363	374	357	346	346	336	334
% Change	0.0%	-4.6%	-3.8%	-1.0%	-5.5%	-8.3%	-8.3%	-11.0%	-11.5%

Figure 123: Total CO_2 Emissions for 2030 Electrification Scenarios



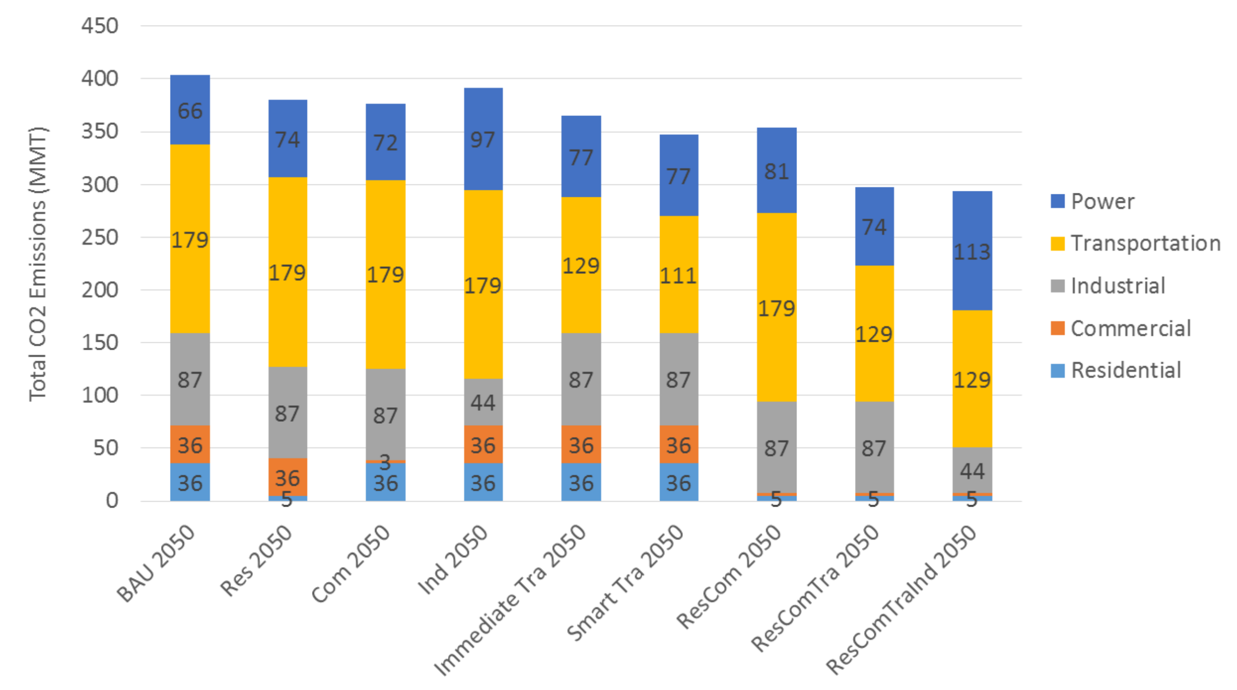
4.3.2.2 GHG Emissions of 2050 Scenarios

Table 12 displays the resulting impacts on CO_2 for the 2050 scenarios relative to the Baseline. As can be seen in Figure 124, net CO2 emission decreases for all scenarios. The largest CO_2 emission savings occurs in the All Sectors Electrification scenario (2050 ResComTraInd Case) as the net CO_2 emissions drop by nearly 55%. The next largest CO_2 emission reductions occur in 2050 ResComTra and 2050 ResCom Cases with achieving 42.5% and 19.2% net reductions in GHG emissions, respectively.

Table 12: CO2 Emission Reductions after Electrification for 2050 Cases

CA CO2 Emissions Reductions After Electrification (MMTCO2) 2050 Cases									
Cases	**BAU 2050**	**Res 2050**	**Com 2050**	**Ind 2050**	**Immediate Tra 2050**	**Smart Tra 2050**	**ResCom 2050**	**ResComTra 2050**	**ResComTraInd 2050**
Residential	36	**5**	36	36	36	36	**5**	**5**	**5**
Commercial	36	36	**3**	36	36	36	**3**	**3**	**3**
Industrial	87	87	87	**44**	87	87	87	87	**44**
Transportation	179	179	179	179	**129**	**111**	179	**129**	**129**
Power	66	74	72	97	77	77	81	74	113
Total (MMTCO2)	404	380	377	392	365	347	354	297	293
% Change	0.0%	-5.8%	-6.7%	-3.0%	-9.5%	-14.0%	-12.3%	-26.4%	-27.4%

Figure 124: Total CO2 Emissions for 2050 Electrification Scenarios



4.4 Air Quality Impacts

A set of scenarios are analyzed, developing spatially and temporally resolved emissions and simulating the resulting air quality. The reference case – Base Case – is used as the baseline for the analysis of the other scenarios. The baseline emissions inventory used for the analysis presented here is based on the National Emissions Inventory (NEI) for 2005, developed by United States Environmental Protection Agency (U.S. EPA, 2011). The 2005 emissions are then projected to 2020 using statewide growth and control factors reported by the California Air Resources Board (CARB, 2013). All scenarios represent power demand and generation for the horizon year (2020, 2030 or 2050) as well as reductions in emissions from technologies that are electrified (such as natural gas ovens and space heaters). A summer and a winter one-week episode are evaluated for each case, in order to analyze the effects of changing emissions on high ozone (summer) and high particulate matter (winter) formation conditions.

4.4.1 Air Quality Impacts of 2020 Scenarios

Table 13 displays the list of developed cases and emission reductions inherent in each case by sector excluding the power sector. As can be seen, variation in electrification potential for technologies and fuels is not equivalent across sectors and thus significant differences exist in emission reductions; that is to say, the residential and commercial sectors can support a larger penetration of electric technologies and thus achieve higher reductions than the industrial sector. The transportation sector case assumes a moderate penetration of electric light duty vehicles (≈10%) and thus achieves the lowest reduction in sector emissions. Power sector emissions are calculated directly in the modeling methodology and thus are not listed here.

Table 13: Reductions in End-Use Energy Sector Emissions for 2020 Cases

	Sector Emissions Reduction			
Case	**Residential**	**Commercial**	**Industrial**	**Transportation**
2020 Res	29.44%	----	----	----
2020 Com	----	30.77%	----	----
2020 Ind	----	----	5.25%	----
2020 Tra	----	----	----	5.11%
2020 ResCom	29.44%	30.77%	----	----
2020 ResComTra	29.44%	30.77%	----	5.11%
2020 ResComTraInd	29.44%	30.77%	5.25%	5.11%

4.4.1.1 2020 Residential Electrification Case (2020 Res Case)

Summer

Figure 125 displays the difference in maximum 8-hour average ozone in the Summer 2020 Residential case from the Base Case. Generally, impacts on ozone are minor and range from -0.84 to 0.21 ppb; although the majority of perturbations fall between + or - 0.5 to 0.2 ppb. Emission reductions from residential natural gas combustion technologies translate to small improvements that cover large areas of the State. Contrastingly, increased emissions from existing gas power generation results in localized areas of worsening that have higher magnitude than improvements but are highly limited in spatial terms. Additionally, effects of the ozone formation dynamics lead to small increases in tropospheric ozone levels in VOC-limited areas like the South Coast Air Basin (SoCAB) despite decreases in NO_x emissions; however, these are generally not regarded as an air quality detriment.

Figure 125: Difference in Peak Ozone in the Summer 2020 Res Case from the Base Case

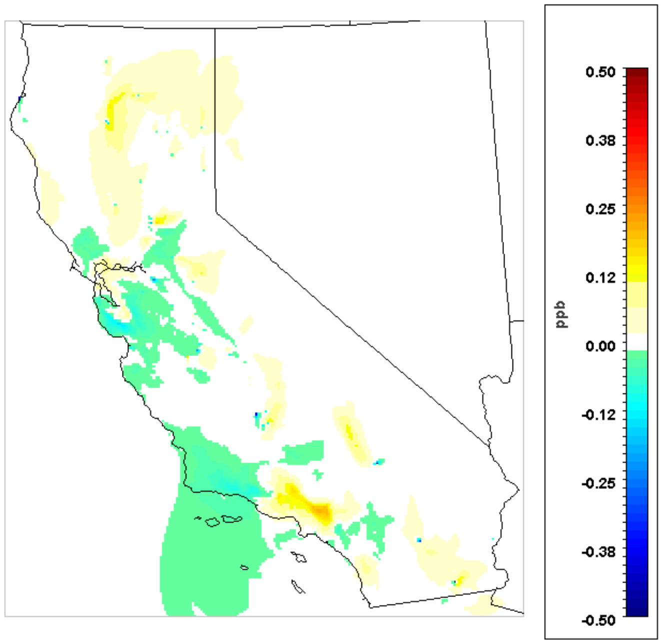
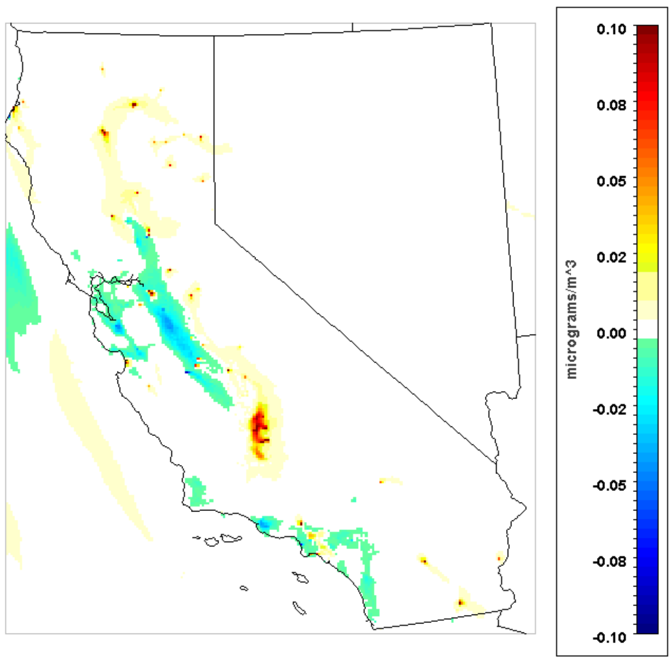


Figure 126 displays the difference in 24-hour fine particulate matter (24-hour $PM_{2.5}$) in the 2020 Res Case from the Base Case. In general, impacts are relatively moderate (range of -0.08 to +0.38 μg/m^3) reflecting the low PM emitting nature of both California's power grid (the lack of coal and high reliance on natural gas) and residential natural gas technologies. However, improvements are observed in the northern portion of the central valley and parts of SoCAB, which have importance as both regions currently experience challenges associated with meeting the health-based Federal standards for $PM_{2.5}$. Conversely, with similarity to spatial ozone patterns localized areas of worsening occur throughout the state, most notably the central valley in the region of Bakersfield, which experiences the largest impacts in terms of magnitude. This is a concern as the area currently is plagued by poor air quality.

Figure 126: Difference in 24-hour average $PM_{2.5}$ in the Summer 2020 Res Case from the Base Case



Winter

Figure 127 displays the difference in maximum 8-hour average ozone in the Winter 2020 Residential Case from the Base Case. Quantitatively, impacts range from -0.36 to +0.75 ppb. In general, trends are similar to the Summer Case—moderate improvements over large areas and localized areas of worsening with higher magnitude but reduced area of impact. However, localized areas of worsening occur at dissimilar locations in winter relative to summer, reflecting the complexity of grid dynamics; for example, the winter case experiences an increase in ozone in SoCAB and the Bay Area while the summer case experiences worsening in the northern central part of the State. Contrastingly, reductions in concentration are observable in the central valley of the State. Essentially, emission reductions in winter are associated with worsening and increased emissions yield reductions in ground-level ozone. Differences in impacts on ozone are expected for summer and winter episodes due to differences in ozone formation dynamics including reduced photolysis resulting from shorter days and lower ambient temperatures. As a result, ambient ozone concentrations are typically much lower in winter relative to summer.

Figure 127: Difference in peak ozone in the Winter 2020 Res Case from the Base Case

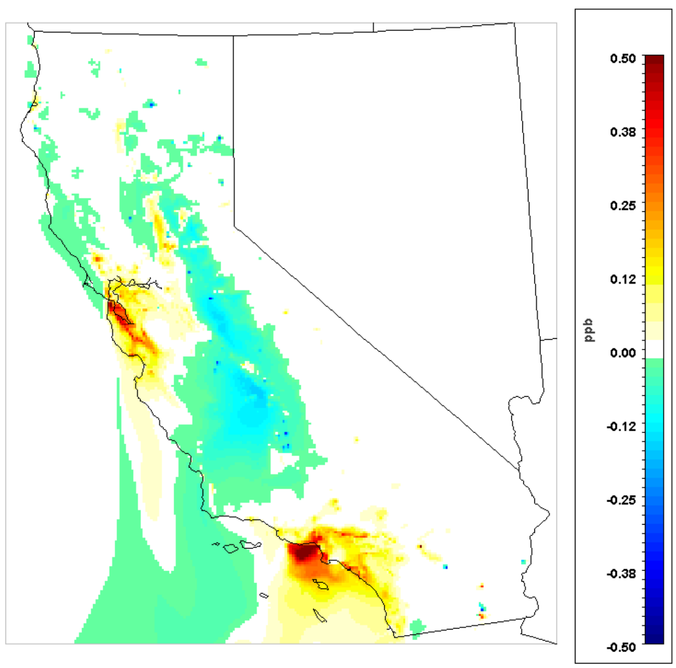
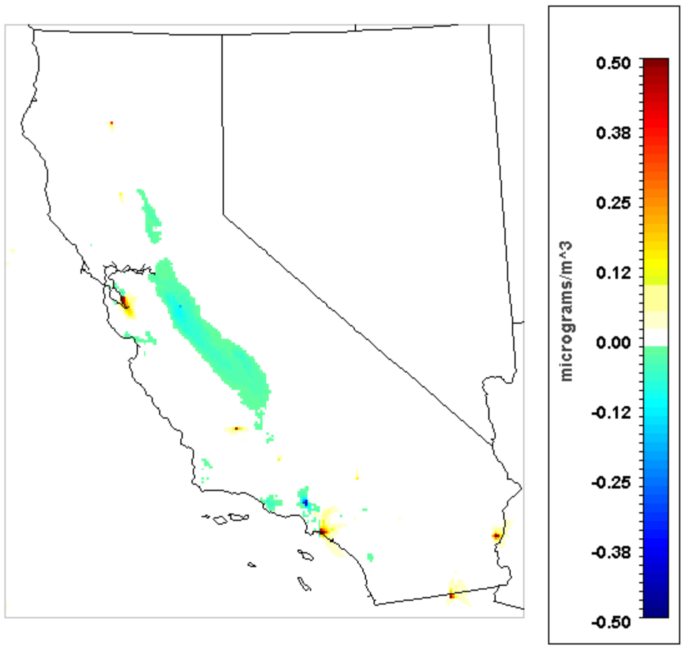


Figure 128 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2020 Residential Case from the Base Case. Impacts are similar to those from the Summer Case and include small to moderate improvements in the central valley in tandem with small areas of worsening co-located to gas generators. Additionally, with similarity to ozone results, differences between summer and winter are evident in locations of worsening and reflect different grid dynamics between the two seasons as well as variation in impacts from residential sector demands and technologies (for example, heating is required in winter while cooling is required in summer), which affects emissions.

Figure 128: Difference in 24-hour $PM_{2.5}$ in the Winter 2020 Res Case from the Base Case



4.4.1.1 2020 Commercial Electrification Case (2020 Com Case)

<u>Summer</u>

Figure 129 shows the difference in maximum 8-hour average ozone in the Summer 2020 Commercial Case from the Base Case. Quantitatively, impacts range from -0.34 to +0.78. Impacts are similar in spatial distribution to those from the Residential Case; that is to say, reductions in concentrations occur over large areas of the study region while some local areas experience worsening. Most notably, impacts are observed in the Bakersfield region including increases in concentrations which are followed by decreases in surrounding areas. This could be a result of reduced ozone scavenging reflecting significant reductions in emissions from the commercial sector in the area. Similar impacts are also observed in SoCAB. Relative to the Summer 2020 Residential Case impacts include larger reductions over much of the State as a result of higher emissions occurring from commercial sector sources. Contrastingly, worsening in and around Bakersfield is higher in the 2020 Commercial Case.

Figure 4-70: Difference in peak ozone in the Summer 2020 Com Case from the Base Case

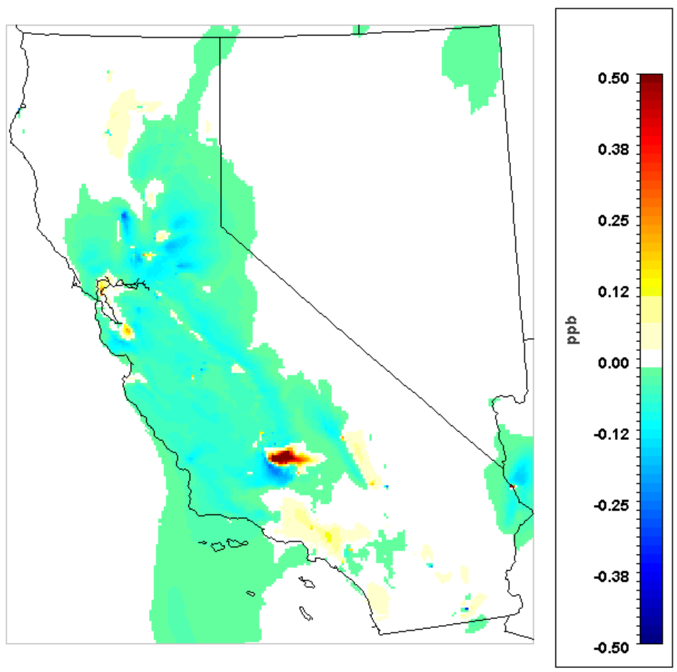
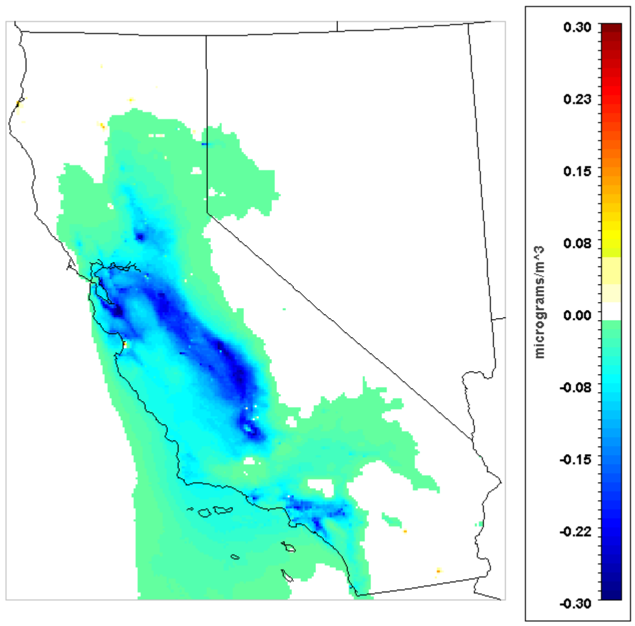


Figure 130 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2020 Com Case from the Base Case. Impacts are characterized largely by reductions in concentrations over large areas of the State. Quantitatively, notable impacts range from -0.38 to +0.37 µg/m^3. Regions of improvement are observable in the Central Valley, SoCAB, the Bay Area, and the Sacramento metropolitan area, reflecting the importance of commercial sector emissions to PM and the low PM emitting nature of California's fossil power generators. As noted for the 2020 Res Case, reductions in PM in the Central Valley have high importance to the State.

Figure 130: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 Com Case from the Base Case



Winter

Figure 131 displays the difference in maximum 8-hour average ozone in the Winter Commercial Case from the Base Case. Peak impacts in the scenario reach -0.21 to +1.50 ppb. Impacts differ significantly relative to the Summer 2020 Commercial Case as a result of variation in ozone formation in winter as discussed above. Contrasting with the Summer Commercial Case, impacts largely include worsening, particularly in and around Bakersfield and highlight how electrification and renewable resource deployment can have varying AQ impacts due to grid dynamics during different seasons. It should again be noted that though ambient concentrations increase from the baseline, overall concentrations remain much lower than those during the modeled Summer episode and thus may not carry the same level of concern. It is also interesting to note that the reductions in commercial sector emissions do not yield improvements in winter in ground-level ozone.

Figure 131: Difference in peak ozone in the Winter 2020 Com Case from the Base Case

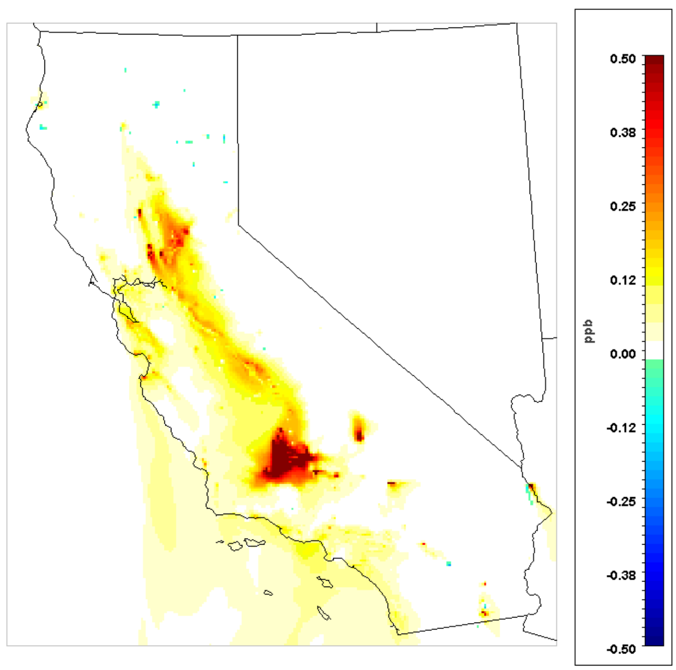
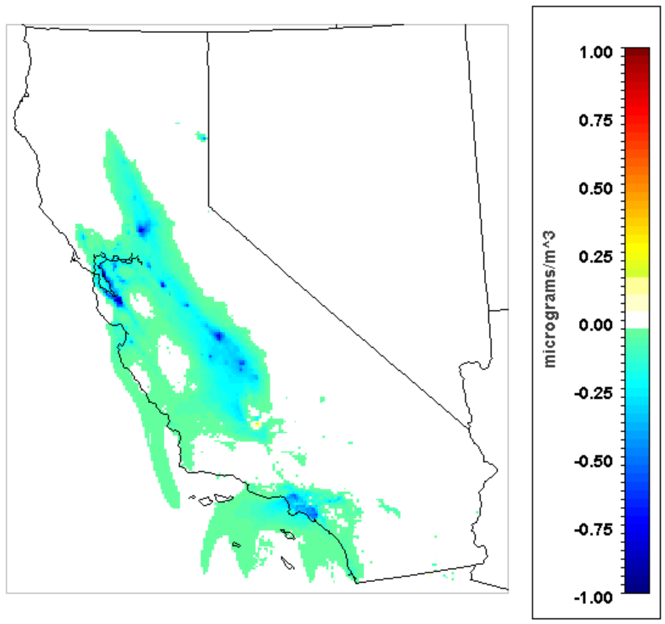


Figure 132 displays the difference in 24-hour $PM_{2.5}$ in the Winter Commercial Case from the Base Case. Quantitatively, impacts range from -1.09 to +0.24 μg/m³. Impacts are similar to PM impacts in the Summer Commercial Case including notable improvements in the Central Valley, which may have increased importance in winter due to the difficulty many areas in the region experience meeting Federal PM Standards during winter months. Improvements are also observable in the Bay Area and SoCAB.

Figure 132: Difference in 24-hour $PM_{2.5}$ in the Winter 2020 Com Case from the Base Case



4.4.1.2 2020 Residential and Commercial Electrification Case (2020 ResCom Case)

Summer

Figure 134 displays the difference in maximum 8-hour average ozone in the Summer ResCom 2020 Case from the Base Case. Quantitatively, impacts range from -1.00 to +0.83 ppb. As would be expected, the results are fairly additive in terms of both the Summer Residential and Summer Commercial Cases. Larger reductions, although still fairly moderate, occur across the State. Increases in ground-level concentrations adjacent to Bakersfield and in SoCAB are heightened as the scenario includes reductions from both residences and commercial buildings together and thus has a larger power demand.

Figure 134: Difference in peak ozone in the Summer 2020 ResCom Case from the Base Case

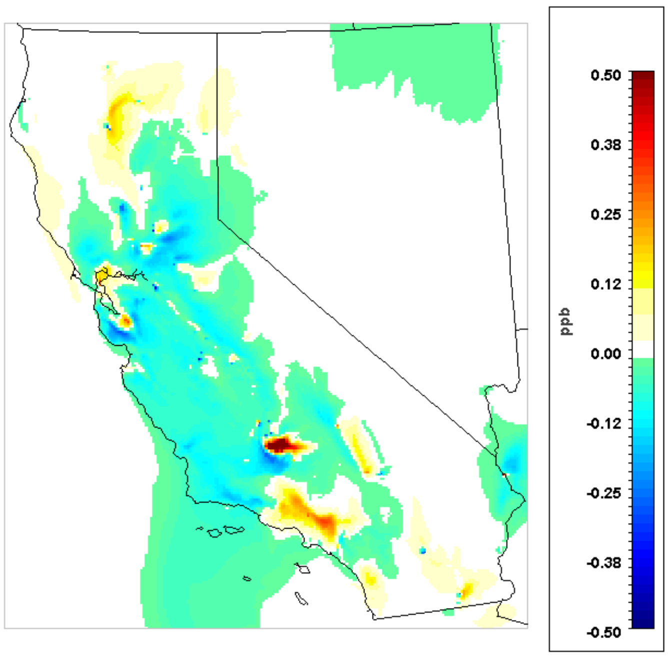
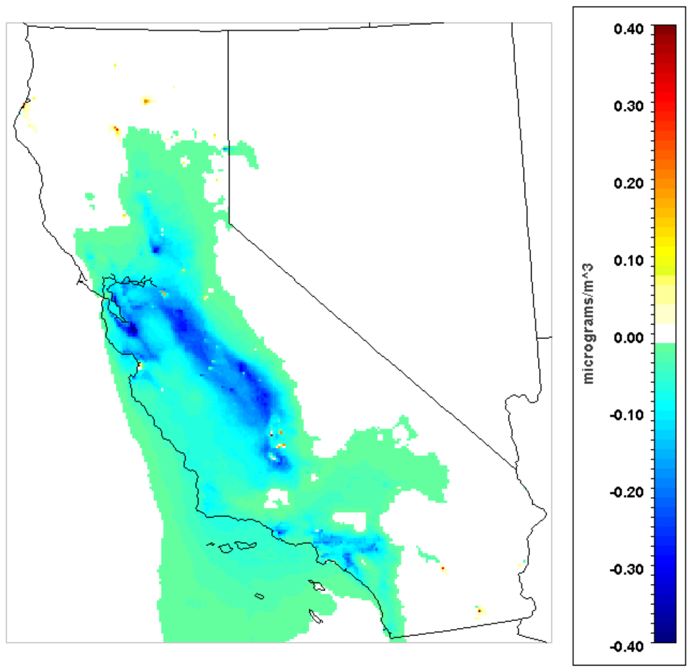


Figure 135 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2020 ResCom Case from the Base Case. Following ozone trends, $PM_{2.5}$ impacts are generally additive when considering both Cases combined and include significant improvement in the Central Valley, SoCAB, Bay Area, and Sacramento regions. Localized worsening is visible in isolated grid cells representing generator locations throughout the State and reflects a larger increase in emissions than in singular cases due to higher novel power demand combined. Quantitatively, impacts range from -0.43 to +0.43 $\mu g/m^3$.

Figure 135: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 ResCom Case from the Base Case



Winter

Figure 136 displays the difference in maximum 8-hour average ozone in the Winter ResCom 2020 Case from the Base Case. Impacts range from -0.53 to +1.60 ppb ozone although the majority of impacts fall under + or -0.8 ppb. Results demonstrate an additive nature with regards to the individual winter Cases in that worsening in ozone concentrations are observed across the State, including several important areas. However, the reduced concern in terms of winter ozone levels mitigates some concerns as discussed above for the individual cases.

Figure 136: Difference in peak ozone in the Winter 2020 ResCom Case from the Base Case

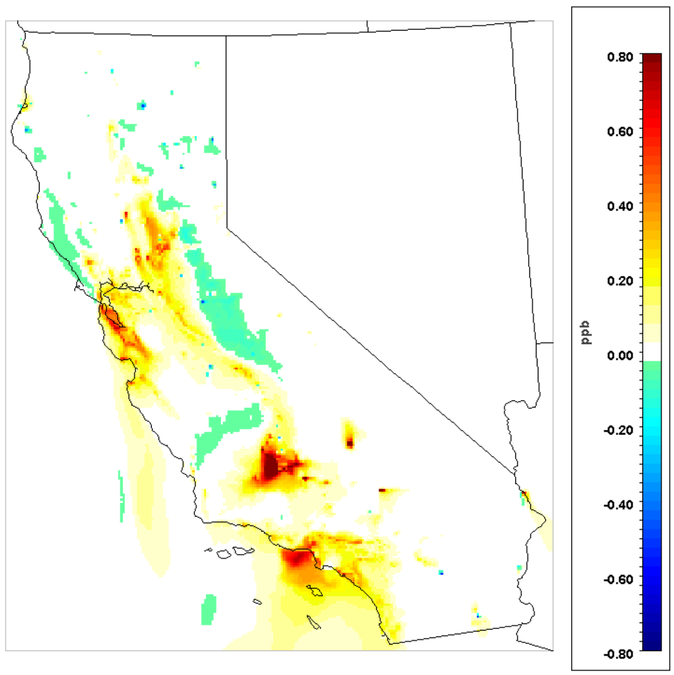
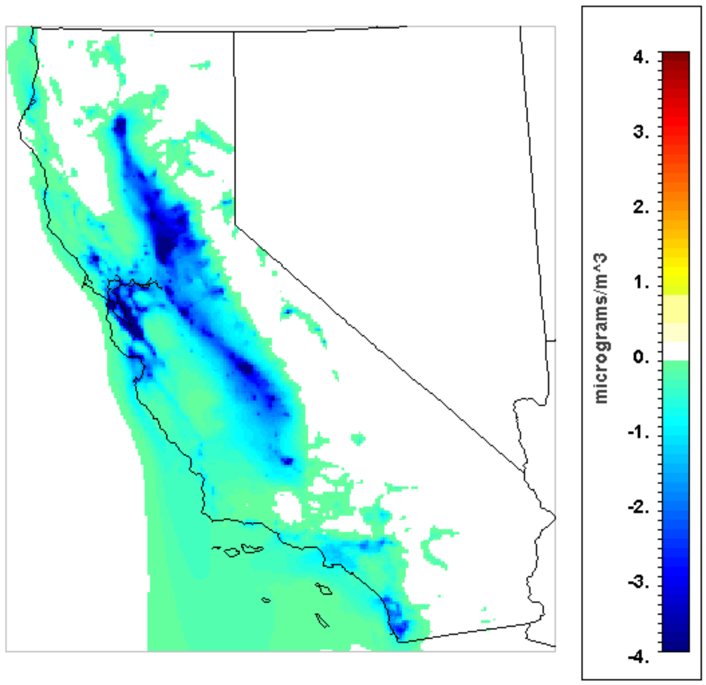


Figure 137 displays the difference in 24-hour PM2.5 in the Winter ResCom 2020 Case from the Base Case. Impacts include significant reductions that occur throughout the State and peak at 7.67 μg/m3 with a range to +0.24 μg/m3. Reductions are large enough to offset any increases from generators and thus the Case achieves a significant air quality benefit to the State in terms of improved winter PM concentrations. As previously stated, the benefits in the Central Valley are particularly important during winter months as PM levels often exceed health-based standards.

Figure 137: Difference in 24-hour $PM_{2.5}$ in the Winter 2020 ResCom Case from the Base Case



4.4.1.3 2020 Transportation Electrification Case (2020 Tra Case)

<u>Summer</u>

Figure 138 displays the difference in ozone in the Summer 2020 Transportation Case from the Base Case. Quantitatively, impacts on maximum 8-hour average ozone range from -0.86 to +0.34 ppb. However, the magnitude of impact is generally moderate with the majority of reductions occurring at -0.5 ppb or less. The penetration of electric light duty vehicles (LDV) at fairly moderate levels (such as a 4% reduction in emissions) yields reductions in ozone in many regions of the State, including urban areas of SoCAB and the Bay Area. Bakersfield also experiences improvement although maximum impacts are may be attributed to the refinery complexes rather than vehicle tail pipe reductions. This is a reflection of both the moderate penetration level of electrification and the improvement in the traditional gasoline internal combustion engine LDVs. Additionally, assumed reductions in petroleum fuel infrastructure including refinery complexes may be the largest driver of air quality benefits.

Figure 138: Difference in peak ozone in the Summer 2020 Tra Case from the Base Case

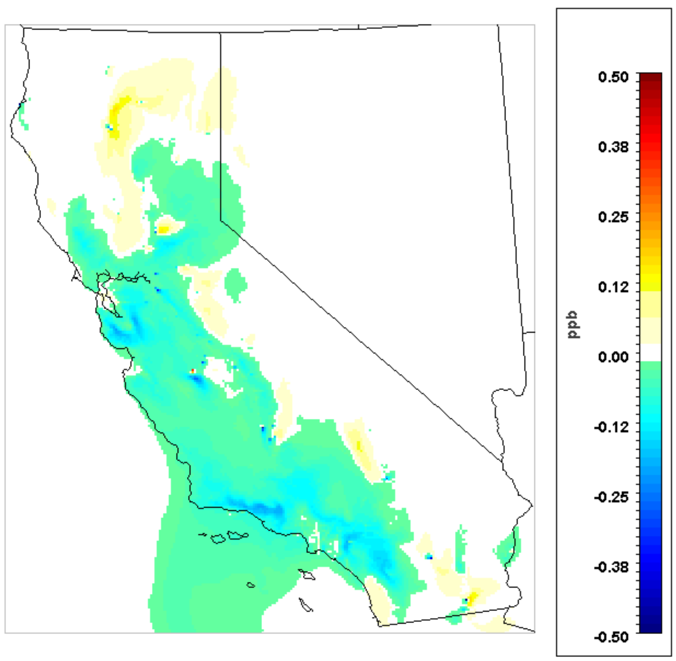
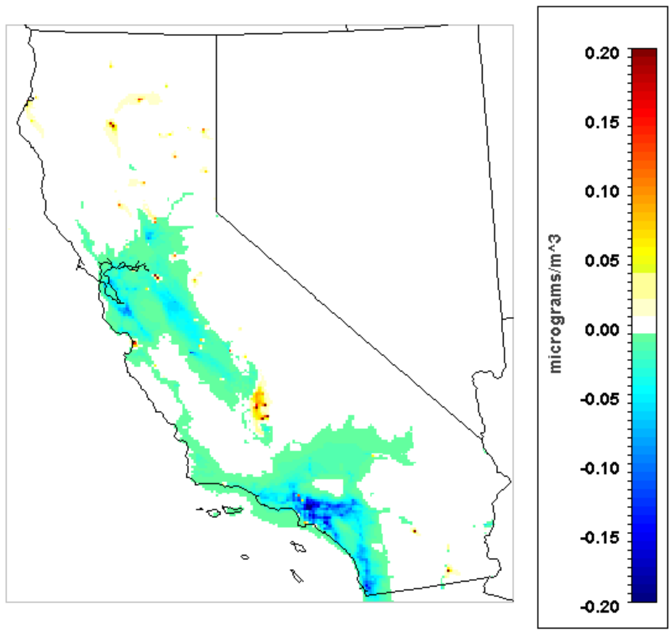


Figure 139 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2020 Transportation Case from the Base Case. Impacts on PM are fairly minor and range from -0.26 to 0.43 μg/m³ with the majority under-0.1 μg/m³ or +0.1 μg/m³. This is expected as LDVs and CA power generators in general do not emit large amounts of PM. Improvements are observed in SoCAB, San Diego, the Bay Area, and the northern area of the central valley. In contrast, localized worsening is observed in Bakersfield and other places in-state. Similarly to ozone, emission from petroleum fuel infrastructure should be considered as a primary driver of impacts in terms of reductions in addition to reductions from vehicle exhaust.

Figure 139: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 Tra Case from the Base Case



Winter

Figure 140 displays the difference in maximum 8-hour average ozone in the Winter 2020 Transportation Case from the Base Case. Impacts range from -0.40 to +0.39 ppb, however the majority of perturbations are minor. Generally, slight worsening occurs in the Bay Area and SoCAB but likely does not represent a significant concern due to winter ozone characteristics. The moderate impacts in the scenario reflect the small penetration of LDVs projected for 2020.

Figure 140: Difference in peak ozone in the Winter 2020 Tra Case from the Base Case

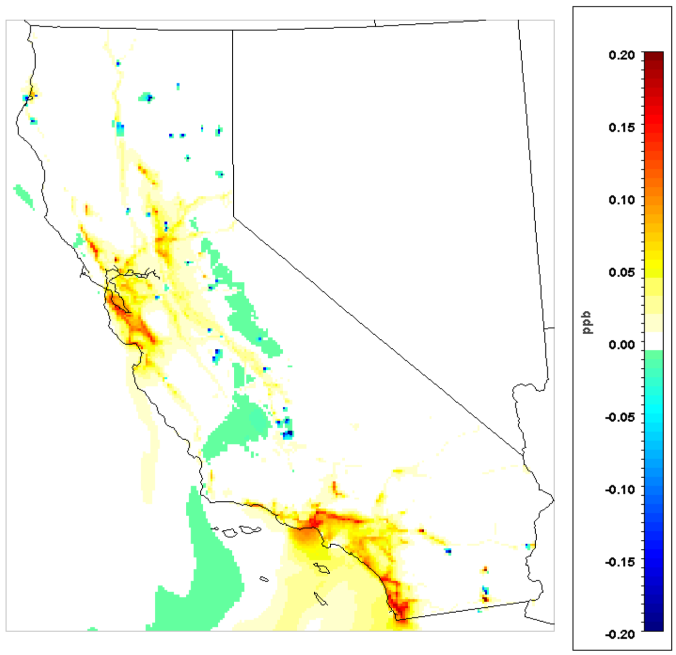
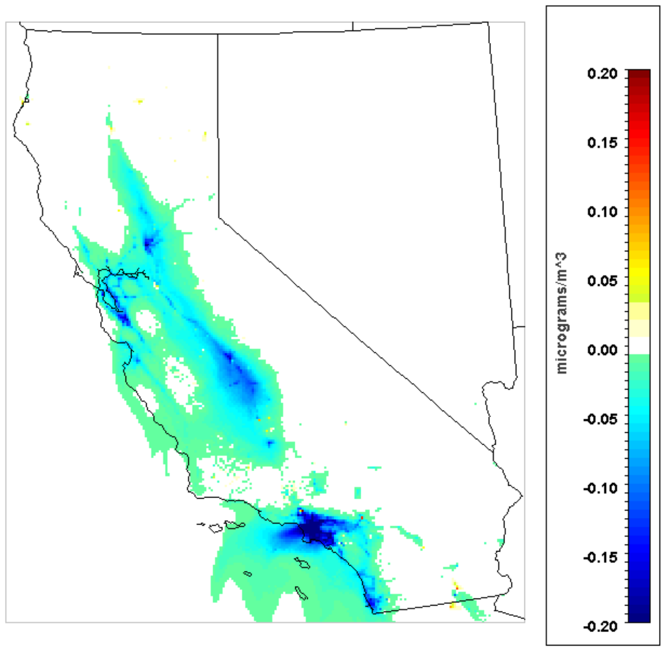


Figure 141 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2020 Transportation Case from the Base Case. In contrast to ozone impacts, significant improvements in $PM_{2.5}$ are observable across all three key regions of the state. Impacts range from -0.37 to +0.29 μg/m³ although improvements dominate any localized worsening from generator increases. Similar to the summer episode, the improvements are relatively substantial relative to the small direct emission reduction inherent in the scenario and it would be expected that a larger penetration of electric vehicles could yield even greater air quality benefits.

Figure 141: Difference in 24-hour $PM_{2.5}$ in the Winter 2020 Tra Case from the Base Case



4.4.1.4 2020 Residential, Commercial, and Transportation Electrification Case (2020 ResComTra Case)

Summer

Figure 142 displays the difference in maximum 8-hour average ozone in the Summer ResComTra 2020 Case from the Base Case. Impacts range from -1.54 to +0.80 ppb although most fall between -1 to +1 ppb. Spatially, impacts follow similar trends to those observed in the individual cases and include moderate improvements over large areas of the state while some areas experience worsening that has higher quantitative values but cover less total area. In particular, the southern Central Valley (adjacent to the Bakersfield region) experiences the highest increase in ground-level ozone concentrations which is a concern given the existing poor air quality conditions the area experiences.

Figure 142: Difference in peak ozone in the Summer 2020 ResComTra Case from the Base Case

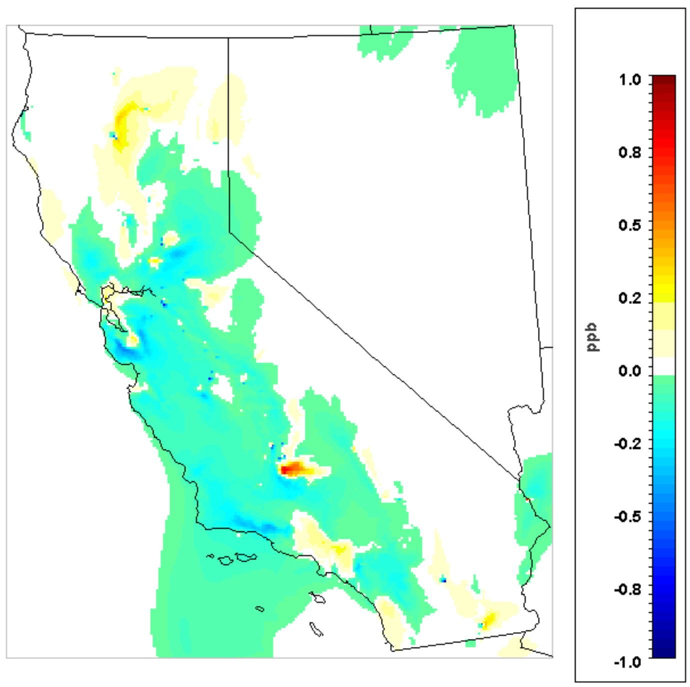
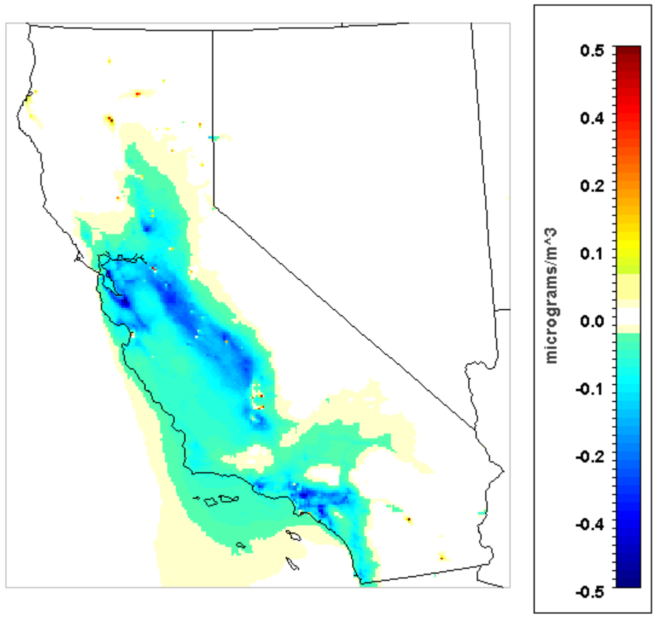


Figure 143 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResComTra 2020 Case from the Base Case. Impacts range from -0.54 to +0.74 μg/m^3. Much of the State experiences improvements although some localized worsening is evident. The key areas in terms of air quality—SoCAB, Bay Area, and Central Valley—all experience general improvements.

Figure 143: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 ResComTra Case from the Base Case



Winter

Figure 144 displays the difference in maximum 8-hour average ozone in the Winter ResComTra 2020 Case from the Base Case. Impacts are generally characterized by small to moderate increases in ozone concentrations with a range of -0.91 to +1.61 ppb. Impacts are additive in nature in relation to the individual cases and include generalized worsening in the SoCAB, Bakersfield, Bay Area, and Sacramento regions. Small areas of moderate reductions also occur.

Figure 144: Difference in peak ozone in the Winter 2020 ResComTra Case from the Base Case

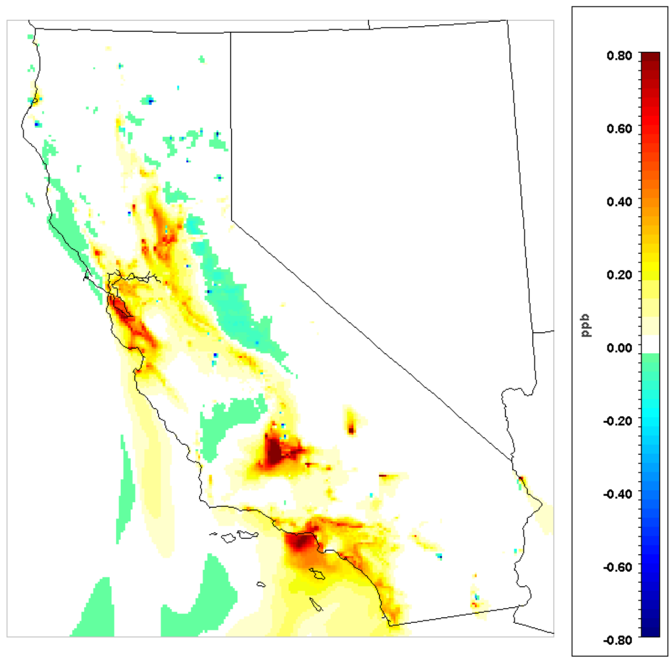
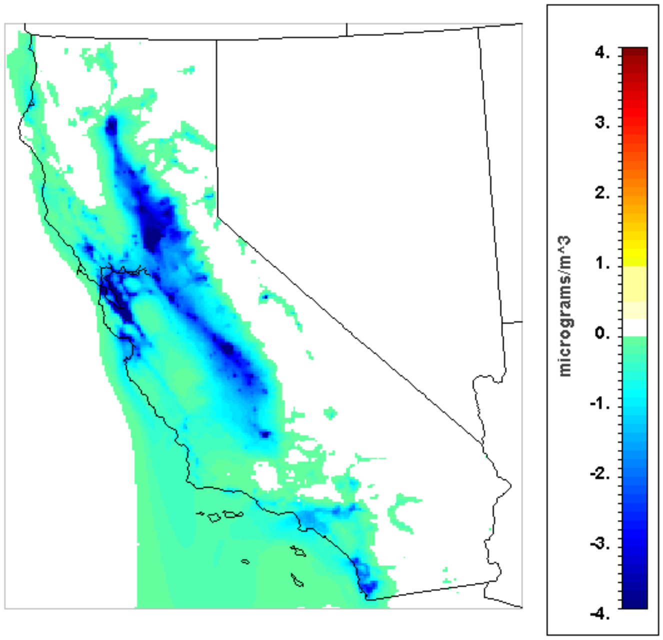


Figure 145 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2020 ResComTra Case from the Base Case. Impacts are characterized largely by significant reductions in PM with notable improvements in the Central Valley, Bay Area, and Sacramento regions. Impacts range from -7.78 to +0.23 $\mu g/m^3$.

Figure 145: Difference in 24-hour PM2.5 in the Winter 2020 ResComTra Case from the Base Case



4.4.1.5 2020 Industrial Electrification Case (2020 Ind Case)

<u>Summer</u>

Figure 146 displays the difference in peak ozone in the Summer 2020 Ind Case from the Base Case. The range of ozone perturbations is equivalent to -8.65 to +7.60 ppb. However, the majority of impacts are relatively small (< + or - 1 ppb) in magnitude reflecting lesser emission reduction potential for the industrial sector relative to others; that is to say, sector emissions are reduced by only 5% relative to the 30% and 29% reductions observed for the Commercial and Residential Cases. Impacts are also highly localized for both reductions and worsening and thus must be considered in terms of local communities that could be impacted.

Figure 146: Difference in peak ozone in the Summer 2020 Ind Case from the Base Case

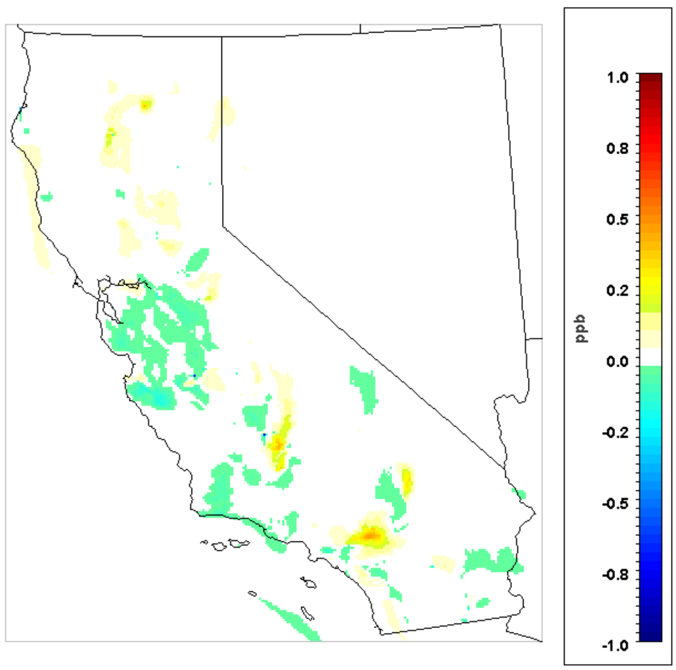
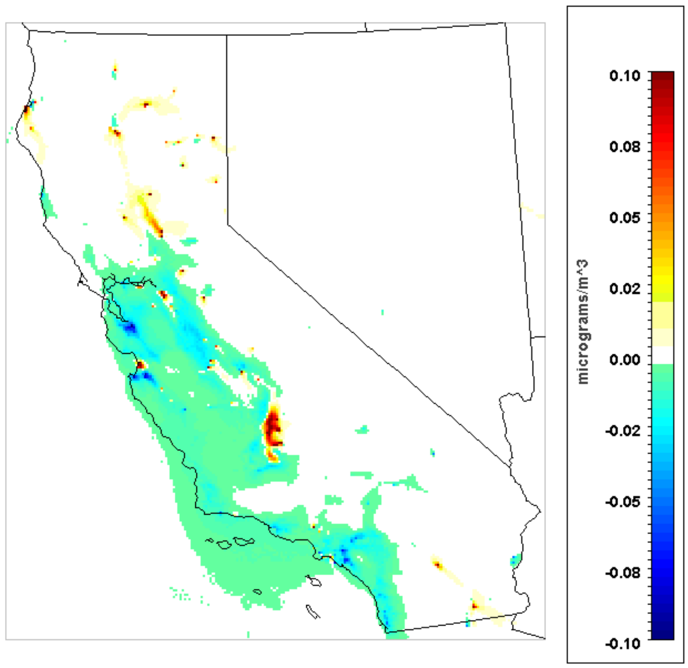


Figure 147 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2020 Ind Case from the Base Case. Spatially, improvements and worsening are observed in many areas of the state in highly localized patterns. Generally, areas of improvement include the Bay Area and SoCAB and areas of worsening include the lower Central Valley and in northern areas of the State including Sacramento. Quantitatively, impacts are fairly minor and range from -0.11 to +0.59 μg/m^3.

Figure 147: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 Ind Case from the Base Case



Winter

Figure 148 displays the difference in peak ozone in the Winter 2020 Ind Case from the Base Case. Impacts are fairly minor as a result of small emission reductions and increases that arise from potential industrial sector electrification. In general, worsening trends are observed at minor magnitudes (ranging from -1.55 to +1.44 ppb), although most impacts are generally less than 0.5 ppb.

Figure 148: Difference in peak ozone in the Winter 2020 Ind Case from the Base Case

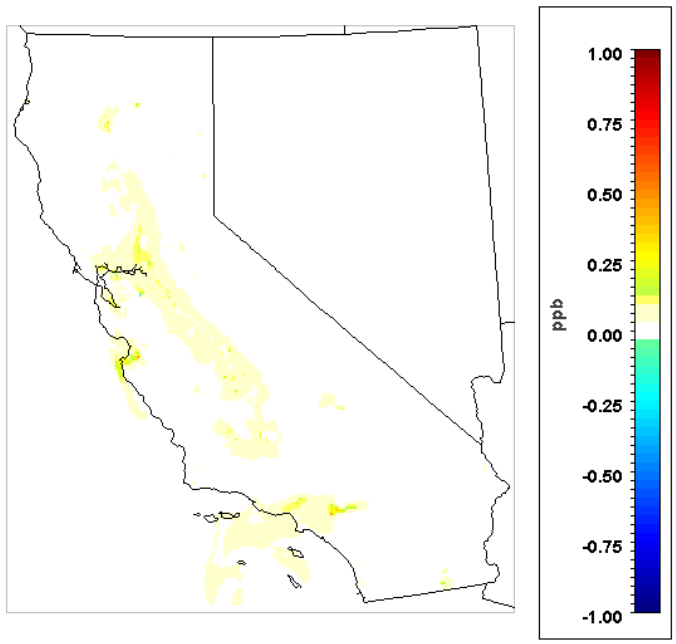
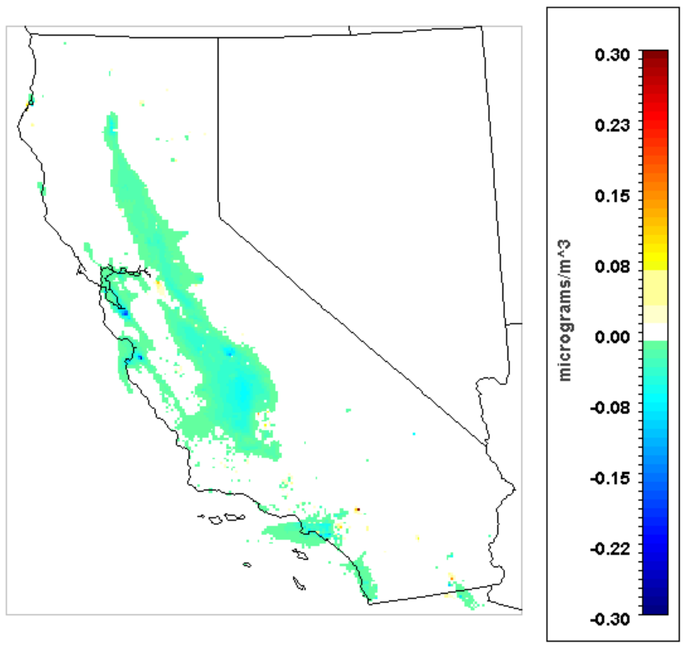


Figure 149 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2020 Ind Case from the Base Case. Though emission reductions are relatively minor, impacts on PM include improvements in the central valley, most notably in and around Bakersfield. Localized areas of improvement also include the Bay Area and SoCAB. The magnitude of improvements is generally less than 0.2 μg/m³ although some localized areas experience reductions around 0.3 μg/m³. Given the small emission, removal impacts are fairly substantial and occur in important areas. Thus, electrification of the industrial sector can provide air quality benefits in terms of winter PM reduction.

Figure 149: Difference in 24-hour $PM_{2.5}$ in the Winter 2020 Ind Case from the Base Case



4.4.1.6 2020 All Sectors Electrification Case (2020 ResComTraInd Case)

Summer

Figure 150 displays the difference in peak ozone in the Summer 2020 ResComTraInd Case from the Base Case. Impacts range from -9.13 to +5.96 ppb. Spatially impacts resemble the patterns of individual cases.

Figure 150: Difference in peak ozone in the Summer 2020 ResComTraInd Case from the Base Case

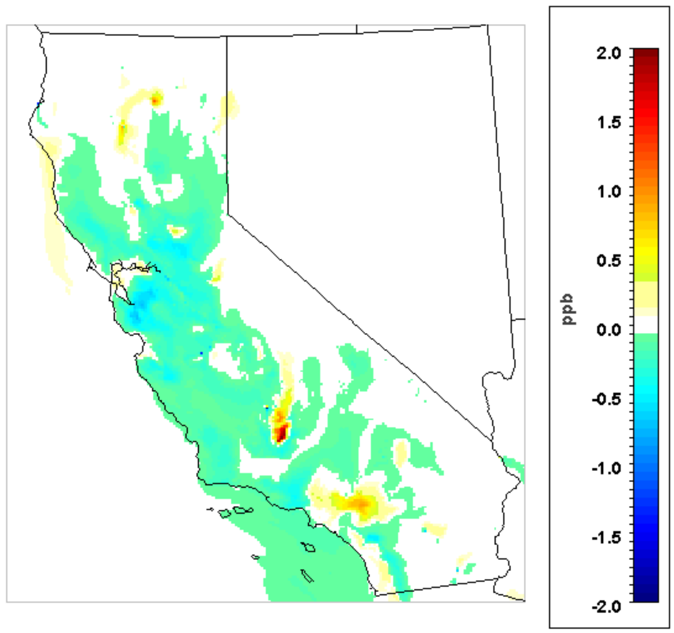
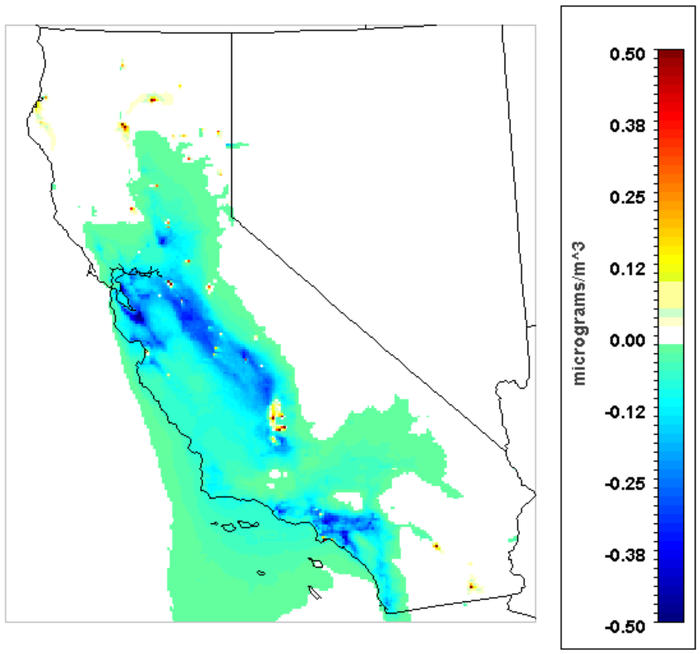


Figure 151 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2020 ResComTraInd Case from the Base Case. As would be expected, the impacts are generally additive for cases and include larger areas of improvement concurrent with localized areas of worsening. Significant areas of improvement with importance include the Bay Area, Central Valley, and SoCAB. Quantitatively impacts range from -0.637 to +1.274 μg/m³.

Figure 151: Difference in 24-hour $PM_{2.5}$ in the Summer 2020 ResComTraInd Case from the Base Case



Winter

Figure 152 displays the difference in peak ozone in the Winter 2020 ResComTraInd Case from the Base Case. Impacts range from -4.12 to +4.14 ppb with the majority of impacts including slight to moderate increases in ambient ozone levels. Spatially impacts resemble those from individual cases and are represented generally as additive.

Figure 152: Difference in peak ozone in the Winter 2020 ResComTraInd Case from the Base Case

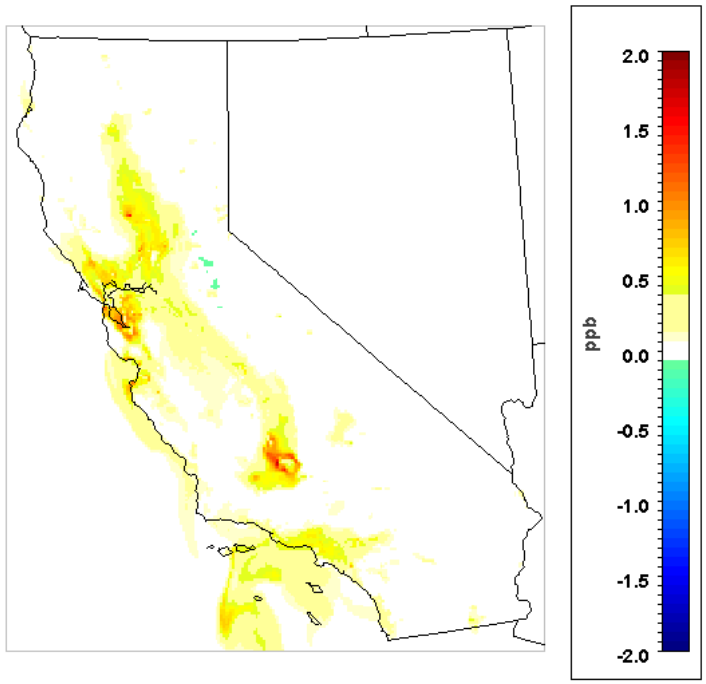
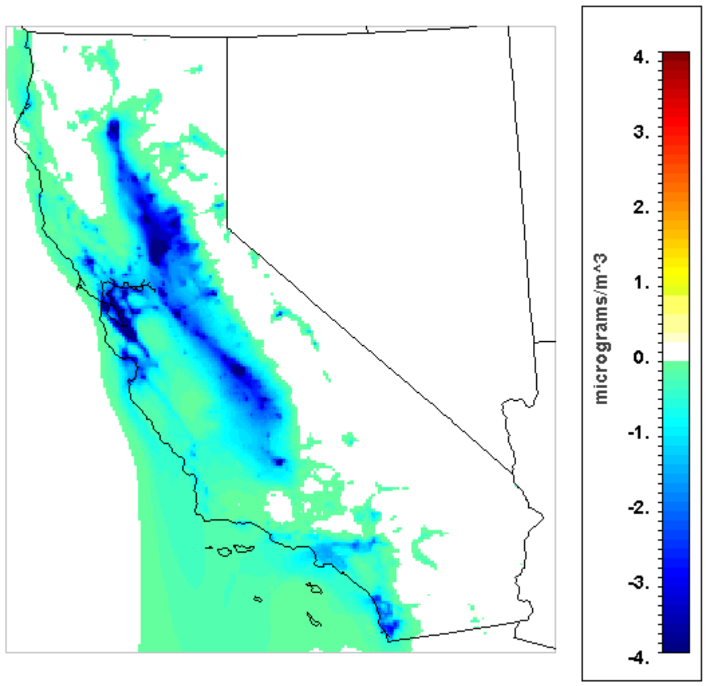


Figure 153 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2020 ResComTraInd Case from the Base Case. Impacts are generally characterized by significant improvements that range from -7.83 to +0.37 μg/m³. With similarity to the Winter 2020 ResComTra Case, the effects of emission reductions in the Winter 2020 ResComTraInd Case yield significant improvements in PM levels in important regions of California.

Figure 153: Difference in 24-hour $PM_{2.5}$ in the Winter ResComTraInd 2020 Case from the Base Case



4.4.1.7 Summary of 2020 Cases

Table 14 displays the peak impacts on 8-hour maximum average ozone and 24-hour average $PM_{2.5}$ for the Summer 2020 scenarios.

Table 14: Summary of peak impacts on 8-hour max ozone and 24-hour PM2.5 for summer 2020 Cases

Summer Case	8-hour Ozone [ppb]	24-hour $PM_{2.5}$ [$\mu g/m^3$]
Res 2020	-1.92 to +1.14	-0.08 to +0.38
Com 2020	-0.97 to +1.75	-0.38 to +0.37
ResCom 2020	-2.47 to +1.78	-0.43 to +0.43
Ind 2020	-2.23 to +1.26	-0.11 to +0.59
Tra 2020	-1.98 to +1.78	-0.26 to +0.43
ResComTra 2020	-4.23 to +1.78	-0.54 to +0.74
ResComTraInd 2020	-6.20 to +1.89	-0.64 to +1.27

Table 15 displays the peak impacts on 8-hour maximum average ozone and 24-hour average $PM_{2.5}$ for the Winter 2020 scenarios.

Table 15: Summary of peak impacts on 8-hour max ozone and 24-hour $PM_{2.5}$ for winter 2020 Cases

Winter Case	8-hour Ozone [ppb]	24-hour $PM_{2.5}$ [$\mu g/m^3$]
Res 2020	-0.36 to +0.75	-7.30 to +0.06
Com 2020	-0.21 to +1.51	-1.09 to +0.24
ResCom 2020	-0.53 to +1.60	-7.67 to +0.24
Ind 2020	-0.50 to +0.40	-0.31 to +0.34
Tra 2020	-0.40 to +0.39	-0.37 to +0.29
ResComTra 2020	-0.91 to +1.61	-7.78 to +0.23
ResComTraInd 2020	-1.37 to +1.69	-7.83 to +0.37

Impacts on PM and ozone are fairly minor for all electrification scenarios in 2020 and reflect a moderate electrification potential from current for many sectors of study. As would be expected, combination cases achieve both the largest improvements from reductions in emissions occurring multiple sectors but also the largest increases from novel power generation due to larger loads (for instance, the Summer ResComTraInd Case experiences both a 6 ppb reduction and 1.2 ppb increase).

Sectors identified as having higher potential for electrification in 2020 include residential and commercial energy use. The electrification of the residential and commercial sectors in tandem with renewable resource deployment moderately improves ozone and $PM_{2.5}$ over some areas of the State in 2020 via emission reductions from gas-fired technologies in those sectors. In particular, residential electrification improves winter-time PM in northern and central California.

Impacts vary between sectors both in terms of magnitude and spatial area of impact, reflecting source distributions, emissions intensities of displaced technologies, electrification potential, etc. In 2020 the industrial sector case achieves the largest reduction in terms of peak max 8-hour ozone while the commercial sector case experiences the largest peak reduction in 24-hour $PM_{2.5}$. However, peak impacts fail to demonstrate differences in spatial distribution of impacts; that is to say, the transportation case achieves more widespread improvements in ground-level ozone than the industrial case despite having a lower peak value. In the absence of complementary technologies/strategies designed to mitigate increased electricity loads areas of AQ worsening occur for both ozone and $PM_{2.5}$ as a result of increased generator emissions in 2020.

The results highlight the difference in season and pollutant for impacts in scenarios; for instance, PM impacts in winter scenarios are largely beneficial while ozone impacts are often associated with worsening. Contrastingly, both summer ozone and PM benefits and worsening occur. Thus, electrification strategies should take into account seasonal factors to maximize air quality benefits.

4.4.2 Air Quality Impacts of 2030 Scenarios

Table 16 displays the emission reduction values that are applied to base line (Base Case) emissions to develop spatially and temporally resolved emission fields for each 2030 scenario. Emissions are then used as input into CMAQ to conduct air quality simulations, which are then compared to the Base Case to develop difference plot from resulting changes in primary and secondary pollutant species.

Table 16: Reductions in End-Use Energy Sector Emissions for 2030 Cases

	Sector Emissions Reduction			
Case	**Residential**	**Commercial**	**Industrial**	**Transportation**
2030 Res	64.94%	----	----	----
2030 Com	----	64.58%	----	----
2030 Ind	----	----	27.57%	----
2030 Immediate Tra	----	----	----	13.17%
2030 Smart Tra	----	----	----	20.64%
2030 ResCom	64.94%	64.58%	----	----
2030 ResComTra	64.94%	64.58%	----	13.17%
2030 ResComTraInd	64.94%	64.58%	27.57%	13.17%

4.4.2.1 2030 Residential Electrification Case (2030 Res Case)

Summer

Figure 154 displays the difference in maximum 8-hour average ozone in the Summer 2030 Residential Case from the Base Case. Quantitatively, impacts range from -0.96 to +1.85 ppb. In general, impacts are fairly moderate with improvements in regions associated with large urban populations coinciding with high concentrations of residential source emissions and worsening in areas corresponding with generator locations. Concentration reductions are notable in the Bay Area and SoCAB while Northern California experiences worsening.

Figure 154: Difference in maximum 8-hour Ozone in Summer 2030 Res Case from the Base Case

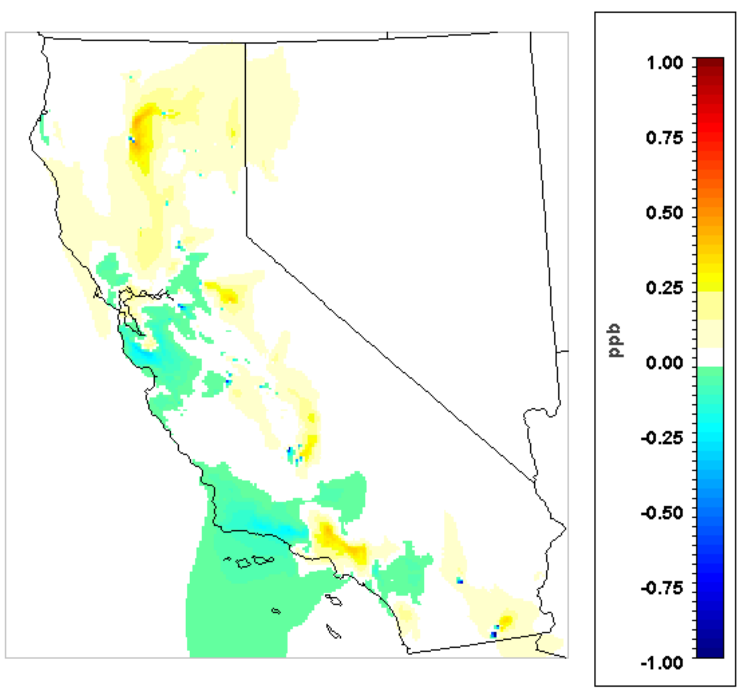
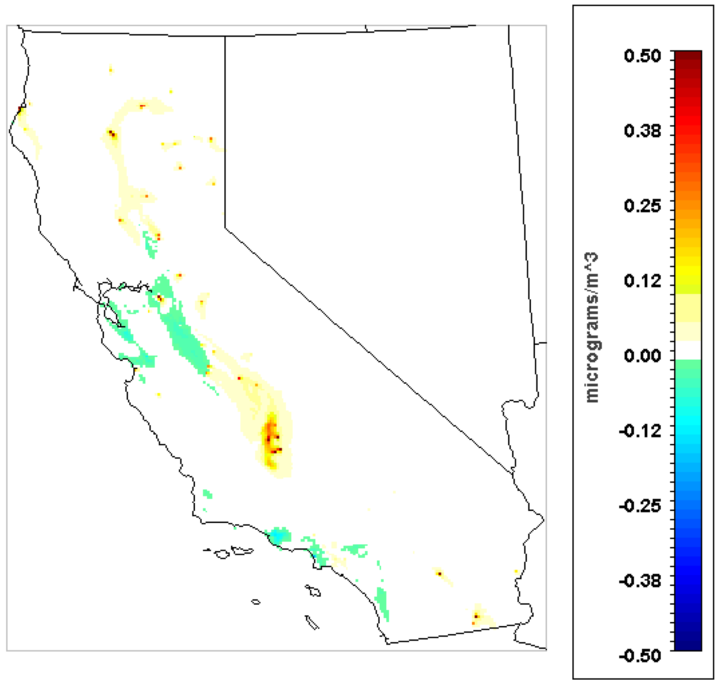


Figure 155 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2030 Residential Case from the Base Case. Quantitatively, impacts range from -0.19 to +1.13 µg/m³. Impacts, both increases and decreases, are fairly minor throughout the State. A notable area of worsening occurs in the Bakersfield region.

Figure 155: Difference in maximum 24-hour $PM_{2.5}$ in winter 2030 Res Case from the Base Case



Winter

Figure 156 displays the difference in maximum 8-hour average ozone in the Winter 2030 Residential Case from the Base Case. Quantitatively, impacts range from -0.78 to +1.82 ppb. Notable areas of concentration increases occur in the SoCAB and the Bay Area. Contrastingly, reductions occur throughout the Central Valley. Generally, impacts tend to occur around 1 ppb and reflect winter ozone formation dynamics.

Figure 156: Difference in 8-hour Ozone in the winter 2030 Res Case from the Base Case

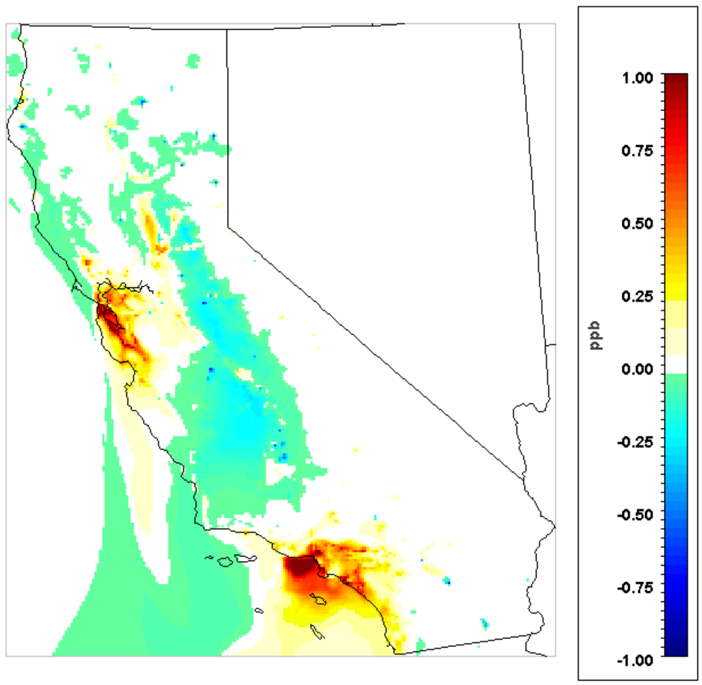
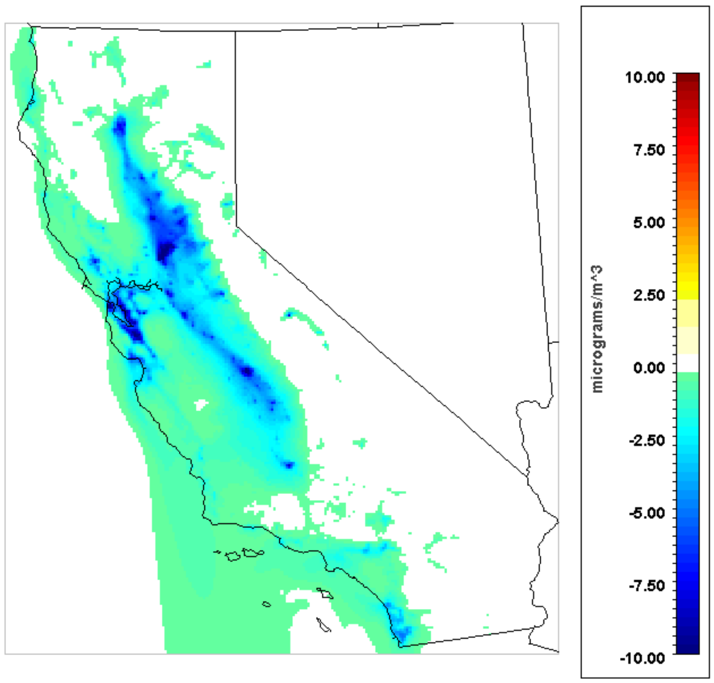


Figure 157 displays the difference in 24-hour $PM_{2.5}$ in the winter 2030 Residential Case from the Base Case. Quantitatively, impacts range from -13.33 to +0.25 μg/m³. Spatially, reductions are most notable in Central California, beginning in Bakersfield and continuing north through the Bay Area and Sacramento. The magnitude of peak reductions is substantial (-13 μg/m³) while no notable areas of worsening occur. Further, as previously mentioned for 2020 Cases reductions in PM in many of these areas is desirable due to currently high winter time PM levels. Thus, the air quality benefits of the winter 2030 Residential Case are prominent.

Figure 157: Difference in 24-hour $PM_{2.5}$ in the winter 2030 Res Case from the Base Case



4.4.2.2 2030 Commercial Electrification Case (2030 Com Case)

<u>Summer</u>

Figure 158 displays the difference in maximum 8-hour average ozone in the Summer 2030 Commercial Case from the Base Case. Quantitatively, impacts range from -1.33 to +0.44 ppb. Significant improvements are visible throughout the State including Sacramento and the Bay Area. SoCAB experiences reductions, although at a lesser magnitude. With similarity to the ozone results, the Bakersfield region experiences worsening, including peak concentration increases due to effects on generator emissions.

Figure 158: Difference in maximum 8-hour average ozone in the Summer 2030 Com Case from the Base Case

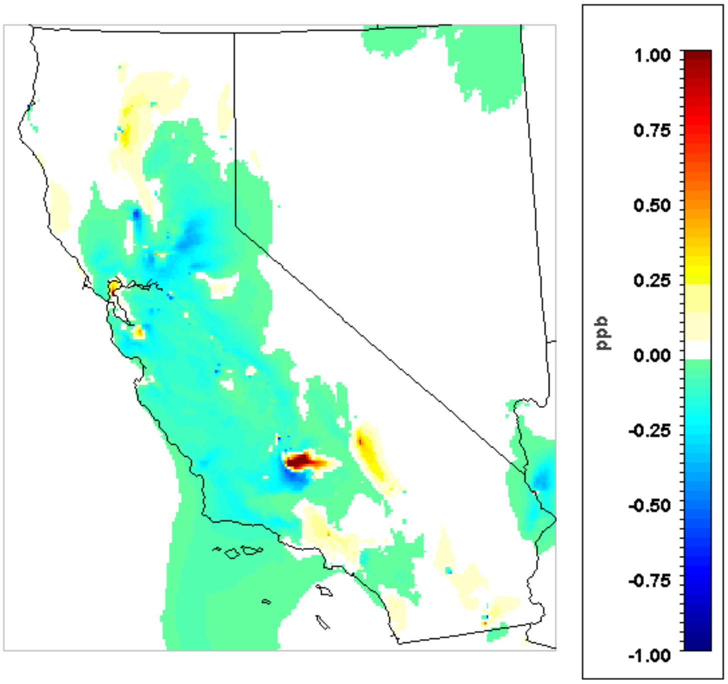
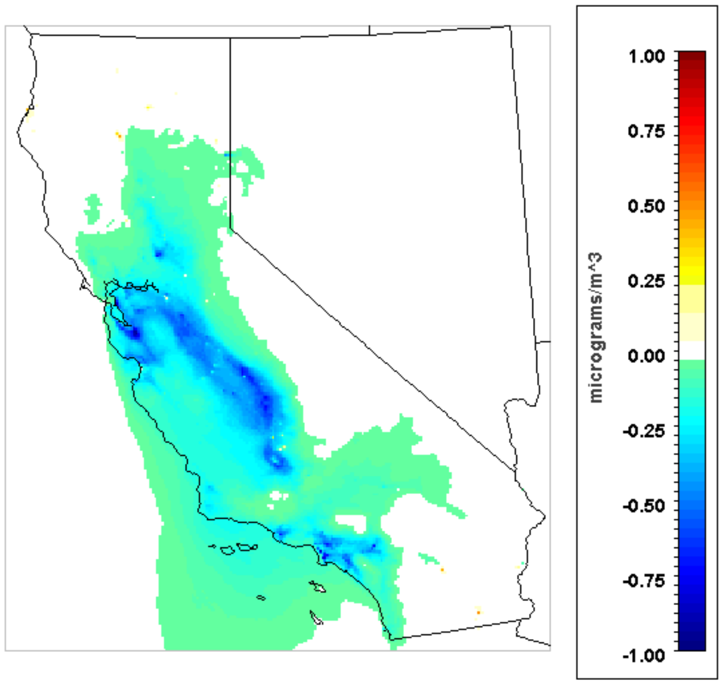


Figure 159 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2030 Commercial Case from the Base Case. Quantitatively, impacts range from -0.99 to +0.48 µg/m^3. Generally, impacts are described by reductions in concentrations that include many important areas of the State—the Bay Area, Southern California Air Basin the Central Valley, and Sacramento. In particular, reductions in the Central Valley cover a large area and include areas experiencing peak reductions.

Figure 159: Difference in 24-hour PM2.5 in the Summer 2030 Commercial Case from the Base Case



Winter

Figure 160 displays the difference in maximum 8-hour average ozone in the Winter 2030 Commercial Case from the Base Case. Quantitatively, impacts range from -0.49 to +3.19 ppb. Generally, impacts include an area of worsening centered in and around Bakersfield and extending north through the Central Valley, the Bay Area, and Sacramento.

Figure 160: Difference in maximum 8-hour ozone in the winter 2030 Com Case from the Base Case

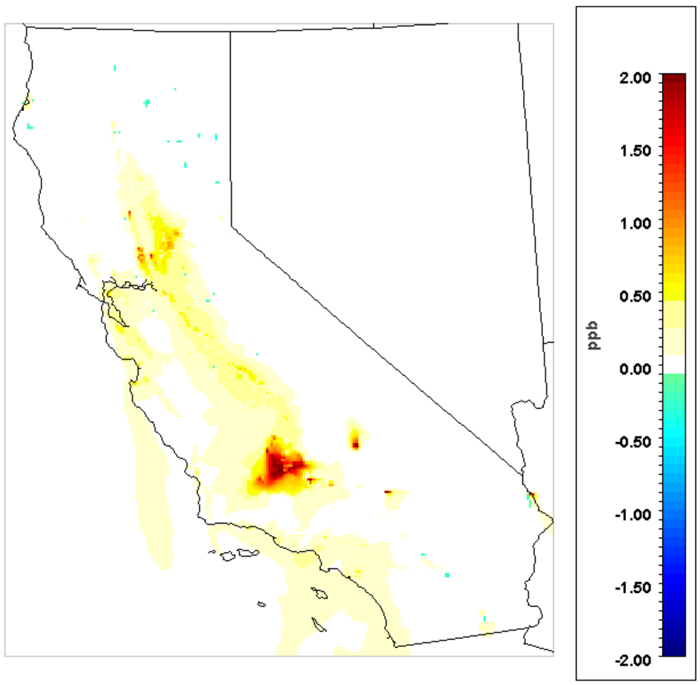
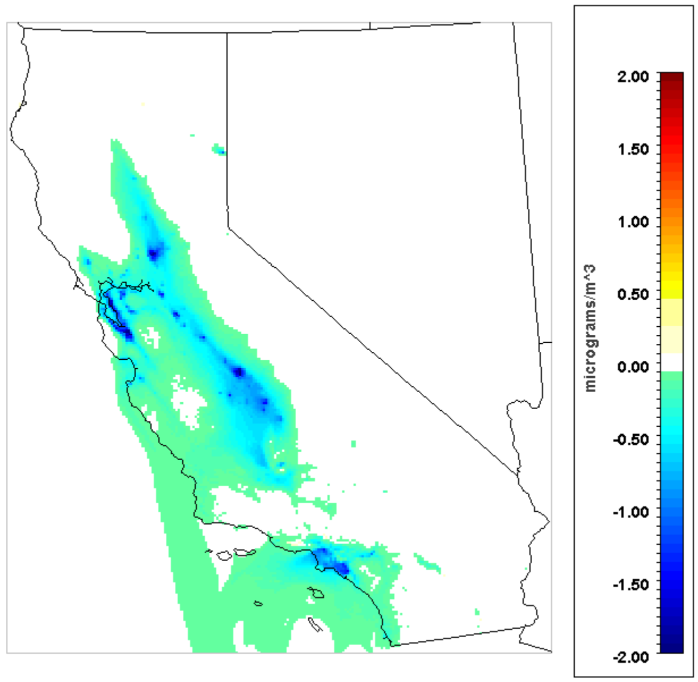


Figure 161 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2030 Commercial Case from the Base Case. Quantitatively, impacts range from -2.69 to +0.19 µg/m^3. Spatially, reductions are most prevalent in the Central Valley, Bay Area, and the SoCAB. While less than the same case for the Residential sector, no significant areas of worsening occur and the outcome of the Winter Com2030 case largely represents an air quality improvement for $PM_{2.5}$. The case also serves as a good example of the reversal of impacts in winter relative to summer for both ozone and PM.

Figure 161: Difference in 24-hour $PM_{2.5}$ in the winter 2030 Com Case from the Base Case



4.4.2.3 2030 Residential and Commercial Electrification Case (2030 ResCom Case)

<u>Summer</u>

Figure 162 displays the difference in maximum 8-hour average ozone in the Summer ResCom 2030 Case from the Base Case. Quantitatively, impacts range from -2.24 to +1.93 ppb. Impacts are generally additive to the two singular cases (residential and commercial), and include large areas of improvement with a lower magnitude (less than or equal to 0.5 ppb). In contrast, localized worsening occurs with a higher magnitude (1 to 2 ppb). A notable area of increase includes Bakersfield and the Northern area of the state.

Figure 162: Difference in maximum 8-hour ozone in summer 2030 Res Com Case from the Base Case

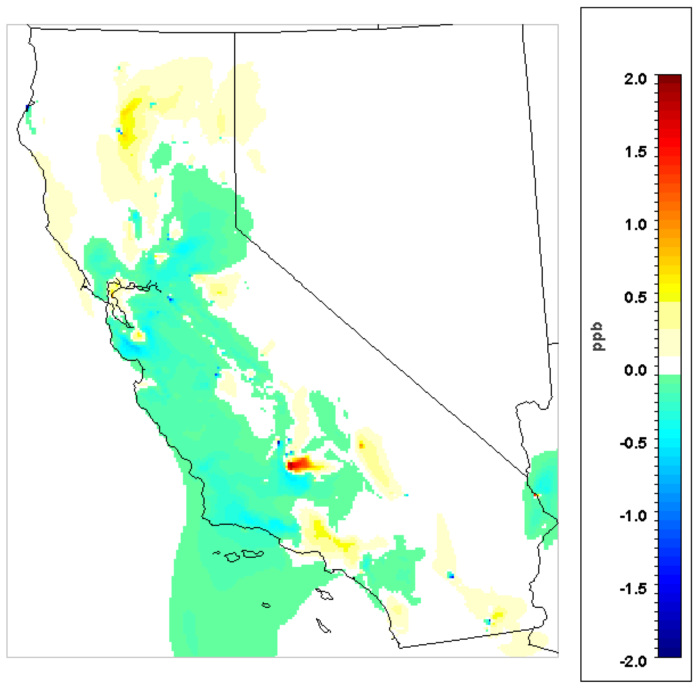
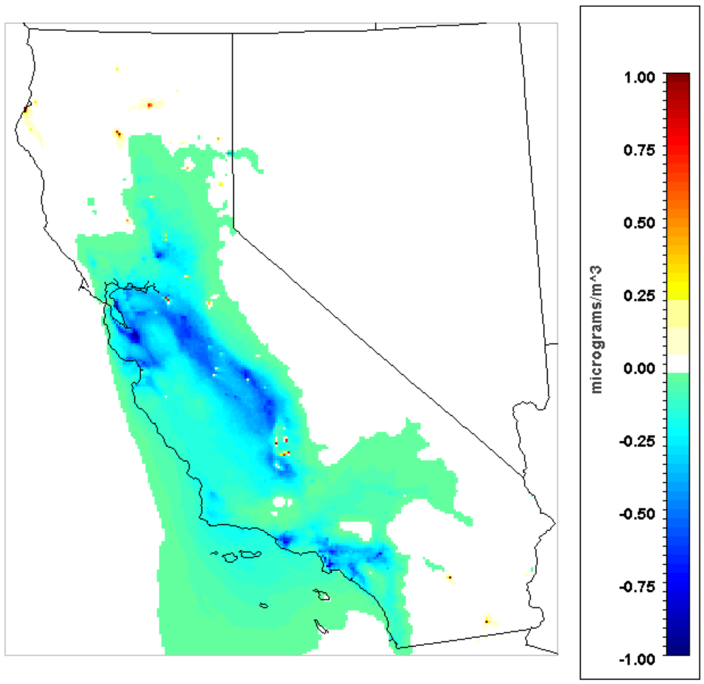


Figure 163 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResCom 2030 Case from the Base Case. Quantitatively, impacts range from -1.07 to +1.42 μg/m³. Impacts are largely characterized by improvements over large areas of the State, including the SoCAB, the Central Valley, and the Bay Area. Small, localized increases occur in the same location as ozone increases but are dominated by improvements.

Figure 163: Difference in 24-hour $PM_{2.5}$ in the summer 2030 Res Com Case from the Base Case



Winter

Figure 164 displays the difference in maximum 8-hour average ozone in the Winter ResCom 2030 Case from the Base Case. Quantitatively, impacts range from -3.56 to +3.31 ppb. Spatially, impacts are fairly additive for the two cases and include prominent areas of worsening in many of the regions of the State that currently experience poor air quality such as SoCAB, the Bay Area, Bakersfied, and Sacramento. However, the wintertime ozone impacts are less of a concern due to seasonal differences discussed in the results section regarding the 2020 winter scenarios.

Figure 164: Difference in maximum 8-hour ozone in winter 2030 Res Com Case from the Base Case

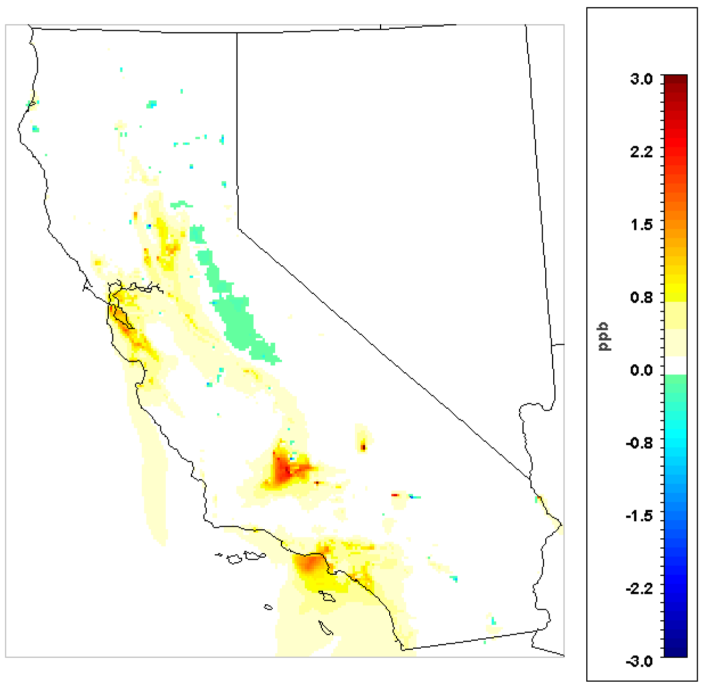
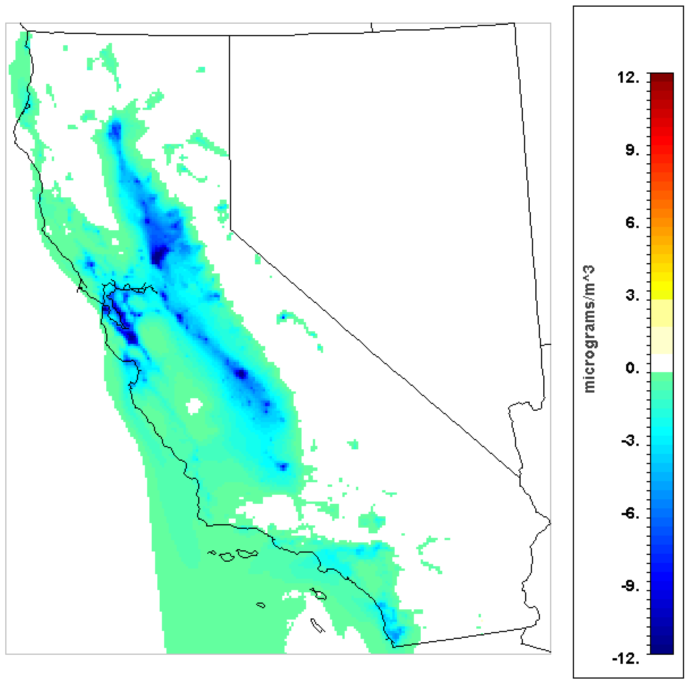


Figure 165 displays the difference in 24-hour $PM_{2.5}$ in the Winter ResCom 2030 Case from the Base Case. Quantitatively, impacts range from -14.51 to +0.45 μg/m^3. As the ResCom Case is largely additive, the largest driver of impacts is associated with emission reductions in the Residential sector. As discussed in the 2030 Residential Case, the magnitude of improvements are substantial and occur in important areas for winter time PM levels such as the Central Valley. Thus, the Winter ResCom2030 Case achieves important improvements in air quality in terms of $PM_{2.5}$.

Figure 165: Difference in 24-hour $PM_{2.5}$ in the winter 2030 Res Com Case from the Base Case



4.4.2.4 2030 Industrial Electrification Case (2030 Ind Case)

Summer

Figure 166 displays the difference in maximum 8-hour average ozone in the Summer 2030 Industrial Case from the Base Case. Quantitatively, impacts range from -4.63 to +1.50 ppb. The significant amounts of novel power required to electrify the industrial sector yield large NO_x emission increases from generators that drive worsening of air quality in some areas of the state. Spatially, impacts include significant areas of worsening in northern sections of the state including the Central Valley, Bay Area, and Sacramento. For the most, part concentration reductions occur in the southern areas of the state including SoCAB from reductions in NO_x associated with major industrial sources.

Figure 166: Difference in maximum 8-hour ozone in summer 2030 Industrial Case from the Base Case

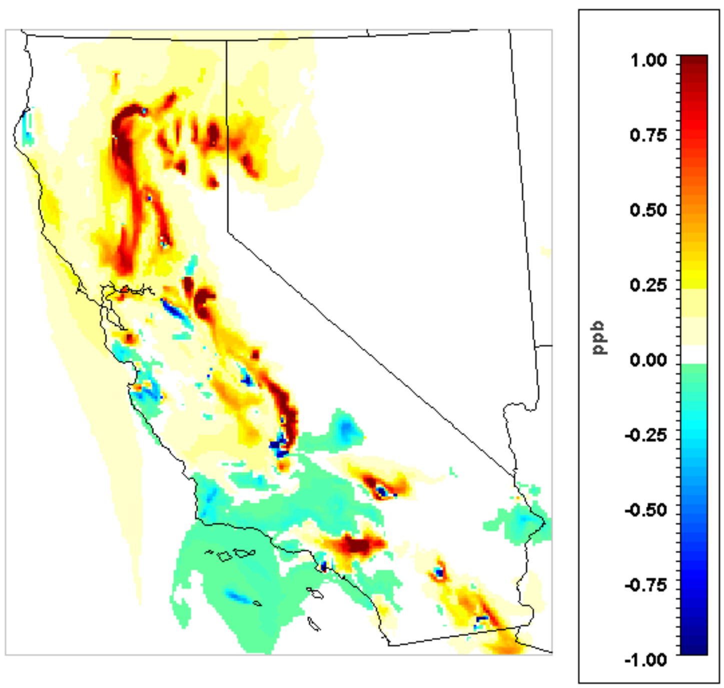
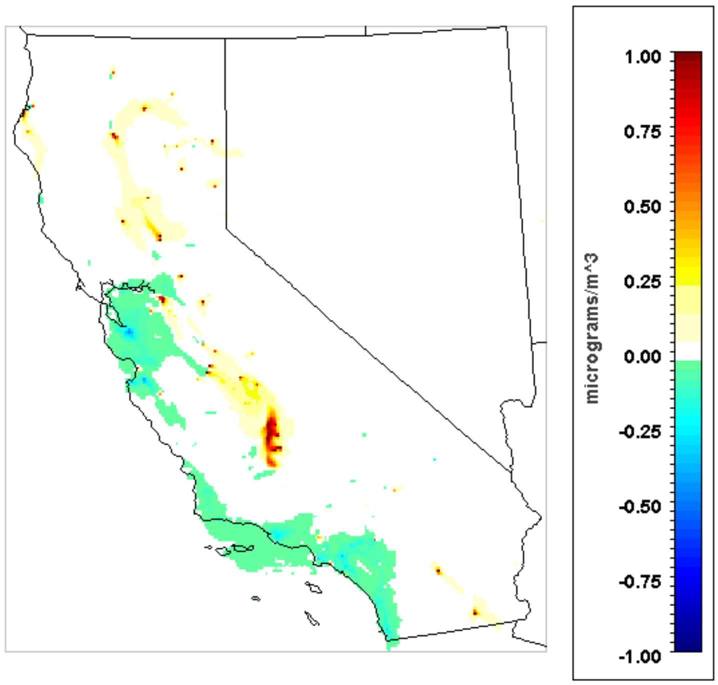


Figure 167 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2030 Industrial Case from the Base Case. Quantitatively, impacts range from -0.48 to +4.34 μg/m³. Slight reductions in $PM_{2.5}$ occur in SoCAB and the Bay Area, largely along the coast. A notable area of increased $PM_{2.5}$ includes the Bakersfield region. Additional increases occur localized to generators in locations throughout the State.

Figure 167: Difference in 24-hour $PM_{2.5}$ in summer 2030 Industrial Case from the Base Case



Winter

Figure 168 displays the difference in maximum 8-hour average ozone in the Winter 2030 Industrial Case from the Base Case. Quantitatively, impacts range from -10.18 to +1.52 ppb. Although peak reductions are highest in terms of achieved reductions, impacts are spatially highly localized to both generator and industrial emission sites. Additionally, worsening occurs in several regions including SoCAB.

Figure 168: Difference in Maximum 8-hour Ozone in winter 2030 Industrial Case from the Base Case

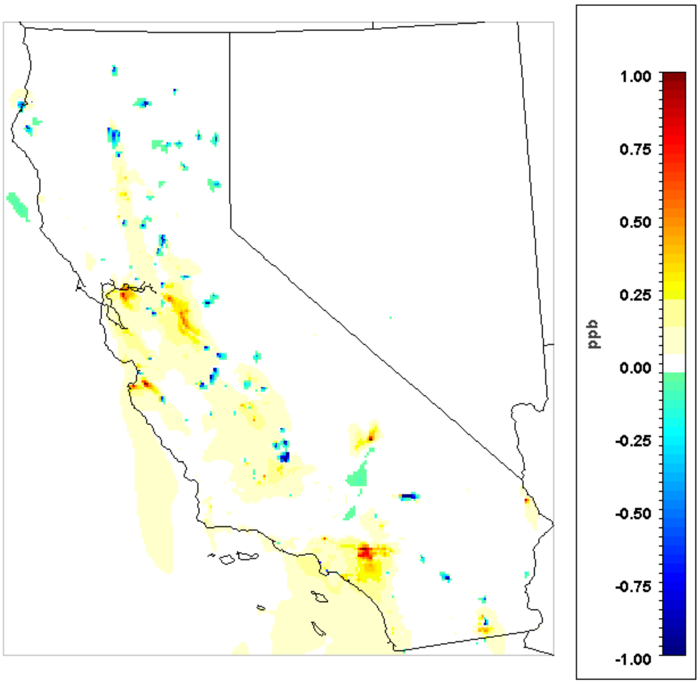
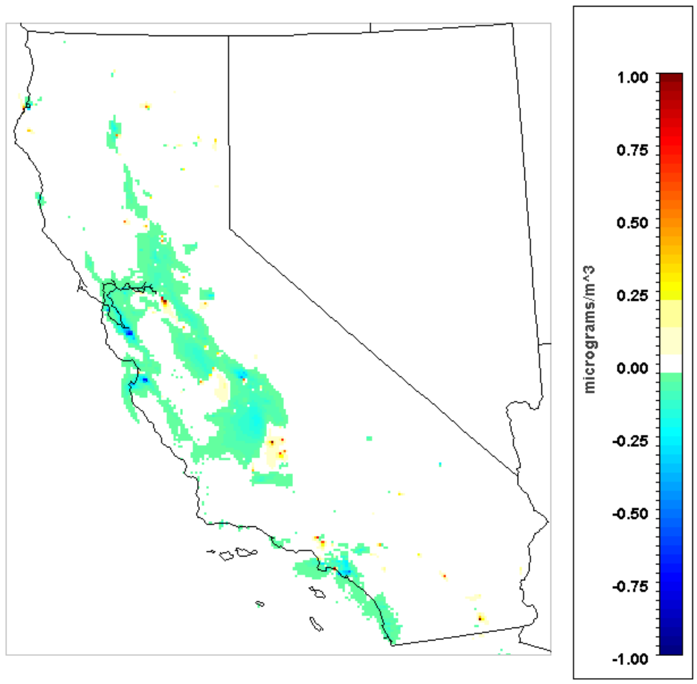


Figure 169 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2030 Industrial Case from the Base Case. Quantitatively, impacts range from 1.21 to 1.29 $\mu g/m^3$. Generally, impacts are fairly minor and include some reductions in the Bay Area, Central Valley, and coastal parts of SoCAB. Worsening is limited to generators near Bakersfield and some other generator locations distributed throughout the State.

Figure 169: Difference in 24-hour $PM_{2.5}$ in the winter 2030 Industrial Case from the Base Case



4.4.2.5 2030 Immediate Transportation Electrification Case (2030 Immediate Tra Case)

<u>Summer</u>

Figure 170 displays the difference in maximum 8-hour average ozone in the summer 2030 Transportation Case from the Base Case. Quantitatively, impacts range from -2.41 to +0.92 ppb. Improvements in ozone occur in areas associated with high vehicle traffic including SoCAB and the Bay Area. Worsening is visible associated with generators in Northern California and some areas of the Central Valley.

Figure 170: Difference in maximum 8-hour ozone in summer 2030 Immediate Transportation Case from the Base Case

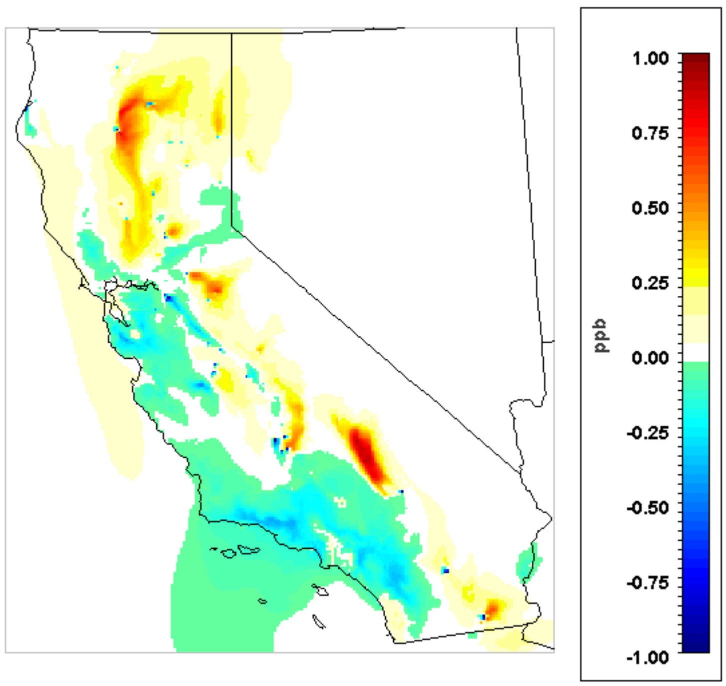
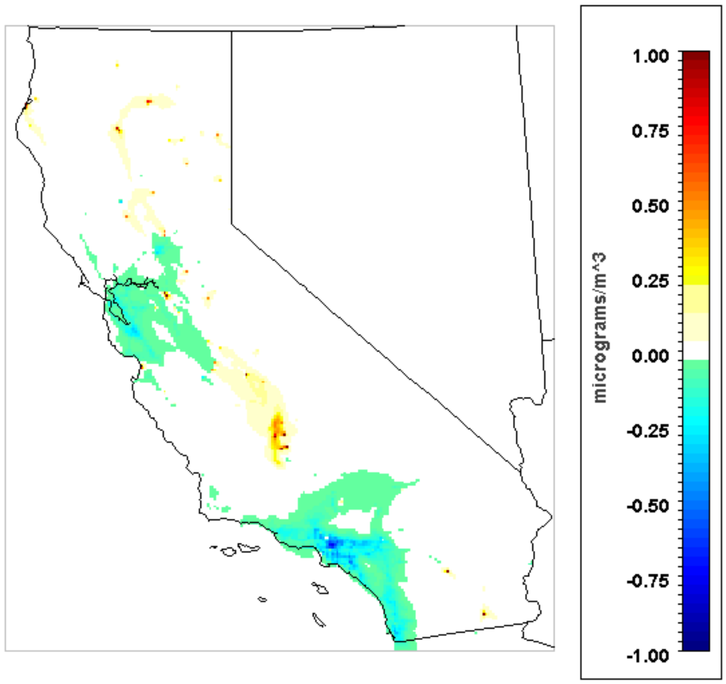


Figure 171 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2030 Transportation Case from the Base Case. Quantitatively, impacts range from -0.76 to +2.04 μg/m^3. Spatial patterns of impacts are similar to those for ozone and include reductions in urban regions like SoCAB and the Bay Area, occurring in tandem with increases in the Central Valley and Northern California.

Figure 171: Difference in 24-hour $PM_{2.5}$ in summer 2030 Immediate Transportation Case from the Base Case



Winter

Figure 172 displays the difference in maximum 8-hour average ozone in the Winter 2030 Transportation Case from the Base Case. Quantitatively, impacts range from -1.63 to +0.67 ppb. Generally, impacts on ozone are fairly moderate and include areas of worsening in the SoCAB and Bay Area and areas of improvement localized to generators sites. Essentially, the winter-time dynamics of ozone result in increases in areas of emission reductions and decreases in locations that experience NO_x increases.

Figure 172: Difference in maximum 8-hour ozone in winter 2030 Immediate Transportation Case from the Base Case

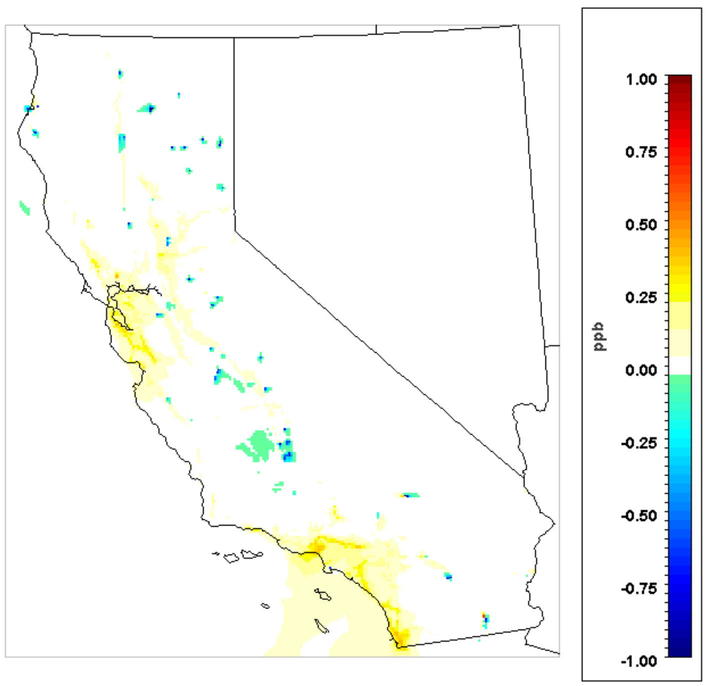
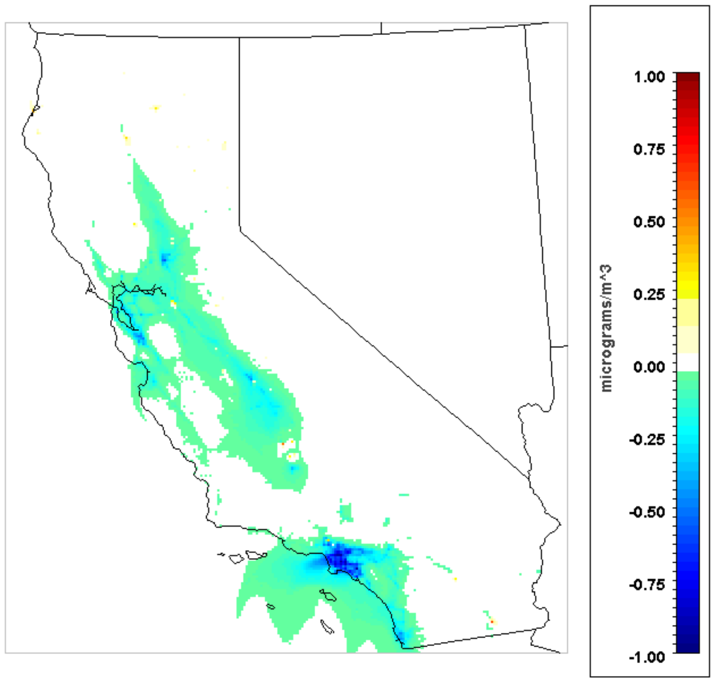


Figure 173 displays the difference in 24-hour $PM_{2.5}$ in the winter 2030 Transportation Case from the Base Case. Quantitatively, impacts range from -1.08 to +0.60 μg/m^3. Impacts are largely beneficial and include reductions in many areas of the State. Most notably, peak reductions occur in SoCAB because of direct vehicle and petroleum refinery emission reductions and represent an important benefit. Additionally, the Central Valley, Bay Area, and Sacramento experience benefits.

Figure 173: Difference in 24-hour PM2.5 in winter 2030 Immediate Transportation Case from the Base Case



4.4.2.6 2030 Smart Transportation Electrification Case (2030 Smart Tra Case)

Summer

Figure 174 displays the difference in maximum 8-hour average ozone in the Summer Tra Smart Charging 2030 Case from the Base Case. Quantitatively, impacts range from -1.89 to +0.63 ppb. Generally, impacts are beneficial and include improvements along coastal urban regions supporting large vehicle populations such as SoCAB, the SF Bay Area, and some portions of the Central Valley. Two notable areas of concentration increases occur, with one being in the northern portion of the state and the other originating from natural gas generators near Bakersfield. The Summer Tra Smart Charging 2030 Case involves a higher penetration of EVs than the Summer Tra 2030 (immediate charging assumption).

Figure 174: Difference in maximum 8-hour ozone in summer 2030 Smart Transportation Case from the Base Case

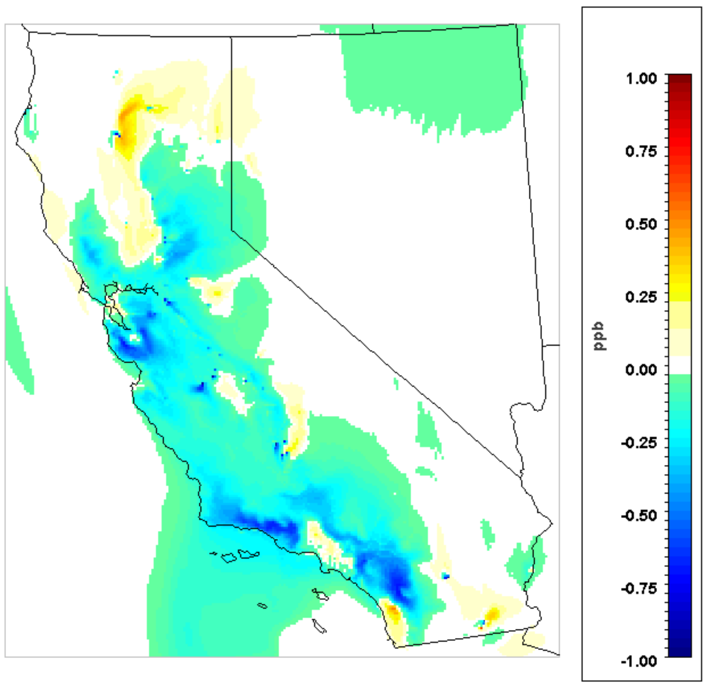
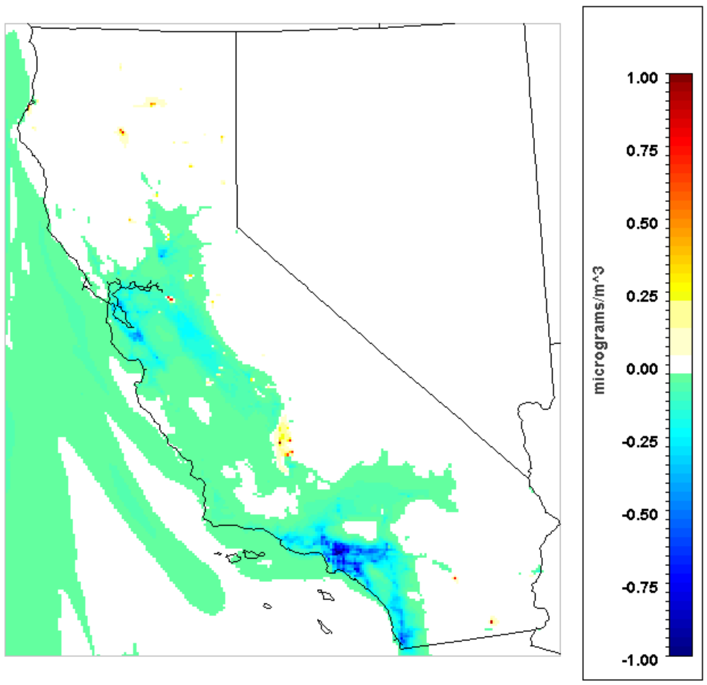


Figure 175 displays the difference in 24-hour $PM_{2.5}$ in the Summer Transportation Smart Charging 2030 Case from the Base Case. Quantitatively, impacts range from -0.96 to +1.02 μg/m^3. Impacts are largely characterized by improvements over large areas of the State, including the SoCAB, the Central Valley, and the Bay Area. In particular, reductions in the SoCAB represent the largest impact in the Case. Small, localized increases occur in the same location as ozone increases but are dominated by improvements.

Figure 175: Difference in 24-hour $PM_{2.5}$ in summer 2030 Smart Transportation Case from the Base Case



Winter

Figure 176 displays the difference in maximum 8-hour average ozone in the Winter Transportation Smart Charging 2030 Case from the Base Case. Quantitatively, impacts range from -0.81 to +0.69 ppb. Spatially, impacts display fairly minor areas of worsening in many of the regions of the State that currently experience poor air quality, i.e., SoCAB, Bay Area, Bakersfied, and Sacramento. However, the winter time ozone impacts are less of a concern due to seasonal differences discussed in the results section regarding the 2020 Winter scenarios.

Figure 176: Difference in maximum 8-hour ozone in winter 2030 Smart Transportation Case from the Base Case

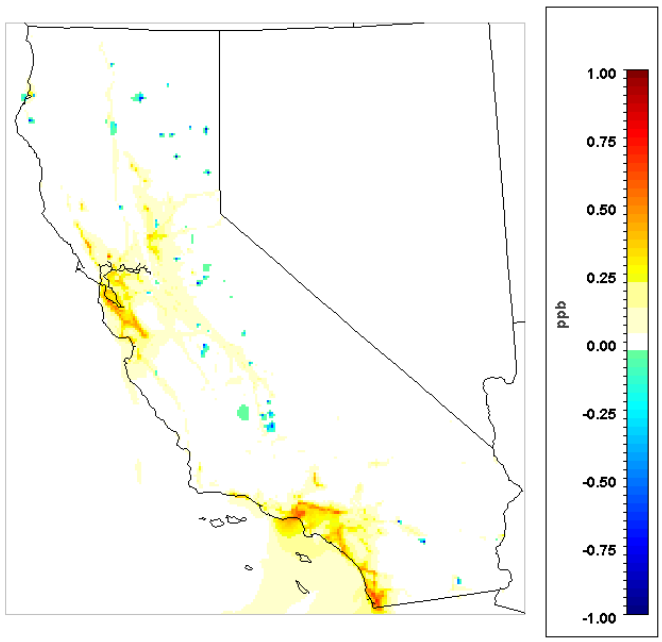
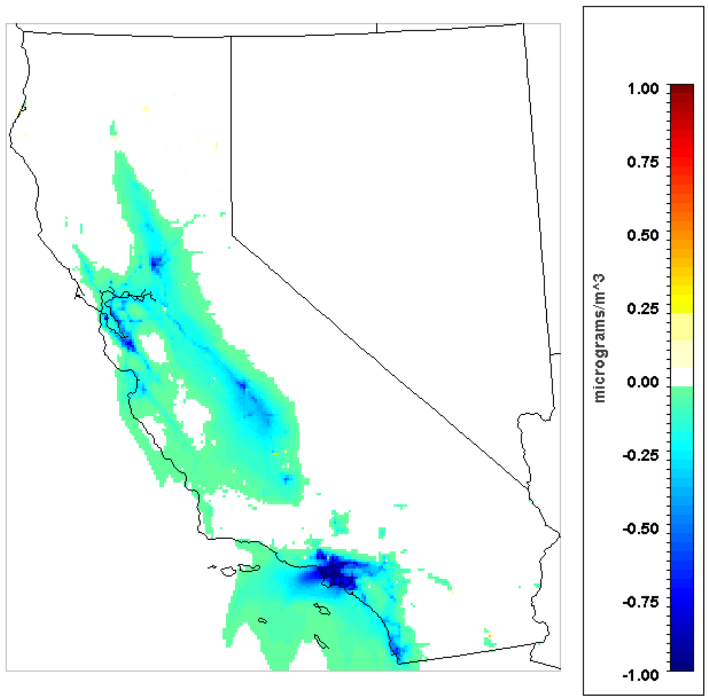


Figure 177 displays the difference in 24-hour $PM_{2.5}$ in the Winter Transportation Smart Charging 2030 Case from the Base Case. Quantitatively, impacts range from -1.65 to +0.39 $\mu g/m^3$. The magnitude of improvements are substantial and occur in important areas for winter time PM levels including the SoCAB, Central Valley, SF Bay Area, and Sacramento Area. Additionally, increases in concentrations are minor to reductions. Thus, the Winter Smart Charging 2030 Transportation Case achieves important benefits to AQ in 2030.

Figure 177: Difference in 24-hour $PM_{2.5}$ in winter 2030 Smart Transportation Case from the Base Case



4.4.2.7 Comparison of 2030 Immediate and Smart Charging Air Quality Impacts

To assess the air quality impacts of smart relative to immediate charging difference plots were generated for the Transportation Smart Charging 2030 Case relative to the 2030 Transportation Case, which assumes immediate charging of vehicles. Thus, the following figures display spatial and temporal distributions of pollutants such that negative values represent enhanced reductions and positive values represent increased concentrations when smart charging is deployed. It should be noted that the Smart Charging Case involves a greater penetration of EVs than the Immediate Charging Case and thus a direct comparison should include that caveat.

Figure 178 shows the difference in maximum 8-hour ozone from smart charging for the Summer 2030 Transportation Case. Quantitatively, impacts range from -0.96 to +1.03 ppb. Impacts are generally represented by improvements over most of the State. Peak improvements occur in the Central Valley with notable impacts in Sacramento and the SF Bay Area additionally. Thus, the smart charging of vehicles can achieve improved AQ benefits relative to immediate charging in terms of summer ozone levels. It perhaps most notable that despite an increase in required electricity for vehicles the Smart Charging Case does not experience higher areas of worsening from power plants. This is due to the charging strategy which avoids charging during peak times and subsequent emissions. Thus, smart charging vehicles can allow for greater vehicle penetrations in tandem with reduced worsening from power plants.

Figure 178: Difference in Maximum 8-hour Ozone between the Smart and Immediate Charging Summer 2030 Transportation Cases

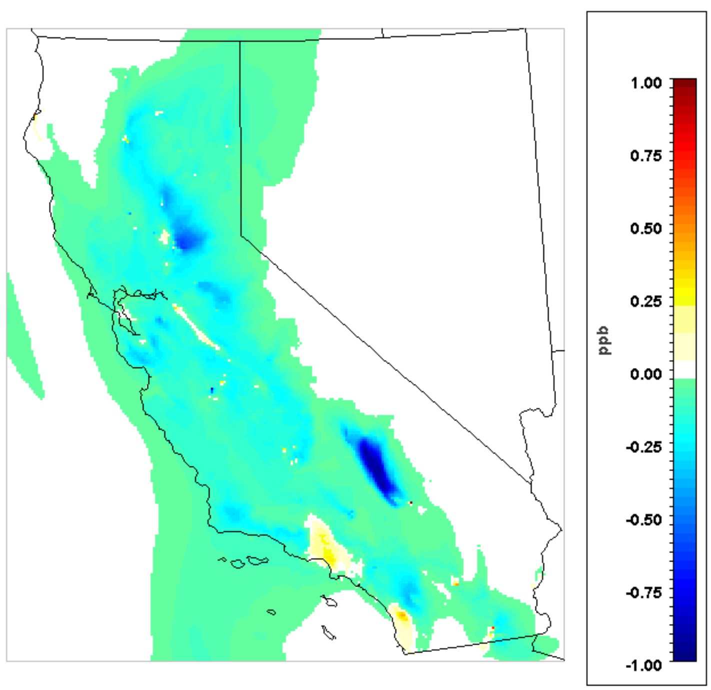


Figure 179 shows the difference in 24-hour $PM_{2.5}$ from smart charging for the Summer 2030 Transportation Case. Quantitatively, impacts range from -0.85 to +0.41 μg/m³. With similarity to the ozone difference, impacts are characterized by improvements in many areas of the State including the SoCAB, Central Valley, and SF Bay Area.

Figure 179: Difference in 24-hour $PM_{2.5}$ between the Smart and Immediate Charging Summer 2030 Transportation Cases

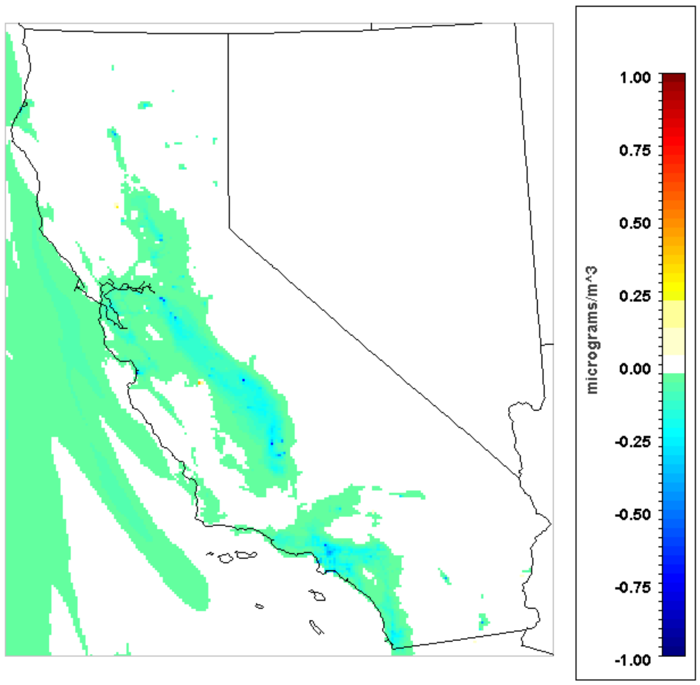


Figure 180 shows the difference in maximum 8-hour ozone from smart charging for the Winter 2030 Transportation Case. Quantitatively, impacts range from -0.82 to +1.68 ppb. Impacts are largely characterized by moderate increases throughout the State. Despite increases, the winter ozone dynamics limit the importance of the effects.

Figure 180: Difference in maximum 8-hour ozone between the Smart and Immediate Charging Winter 2030 Transportation Cases

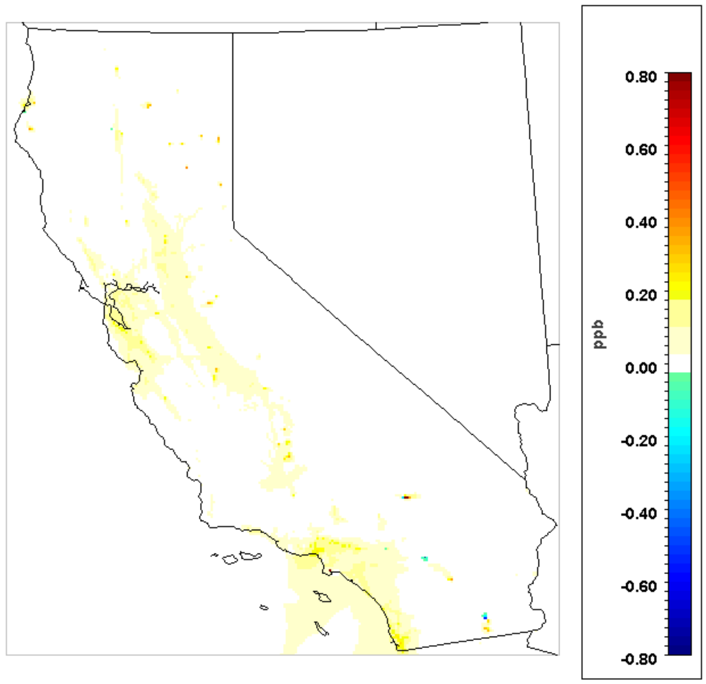
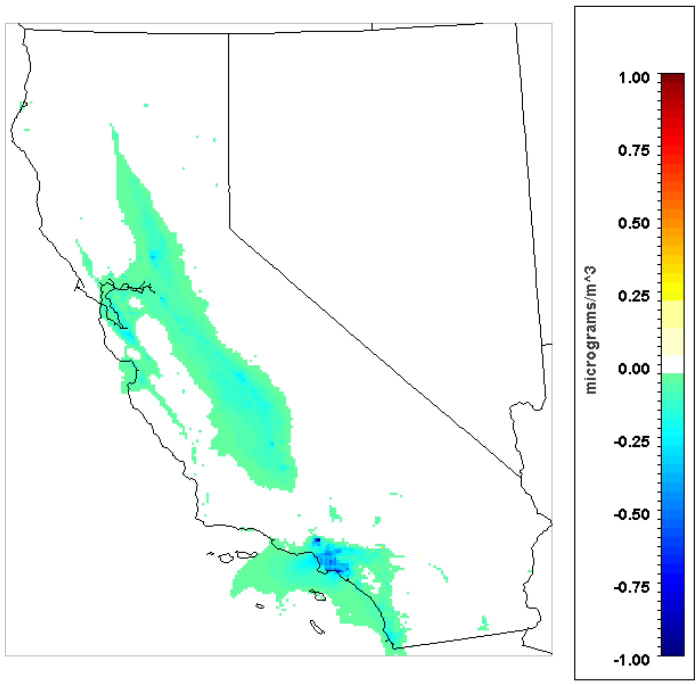


Figure 181 shows the difference in 24-hour $PM_{2.5}$ from smart charging for the Winter 2030 Transportation Case. Quantitatively, impacts range from -1.10 to +0.34 μg/m³. Impacts are largely characterized by improvements in several key areas of the State. Peak impacts occur in the SoCAB which experiences significant improvements in ground-level concentrations. Additional areas of improvement occur in the Central Valley.

Figure 181: Difference in 24-hour $PM_{2.5}$ between the Smart and Immediate Charging Winter 2030 Transportation Cases



4.4.2.8 2030 Residential, Commercial, and Transportation Electrification Case (2030 ResComTra Case)

<u>Summer</u>

Figure 182 displays the difference in maximum 8-hour average ozone in the Summer ResComTra 2030 Case from the Base Case. Quantitatively, impacts range from -4.49 to +1.92 ppb. Impacts are spatially similar to the individual cases and are characterized by areas of improvement throughout the State, including SoCAB and the Bay Area. Increased concentrations occur from generator locations, most notably in Northern California.

Figure 182: Difference in maximum 8-hour ozone in summer 2030 ReComTra Case from the Base Case

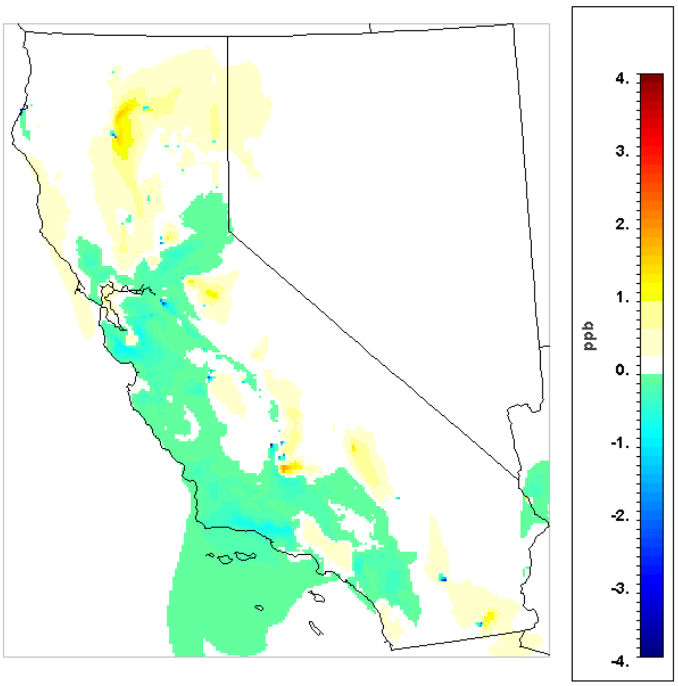
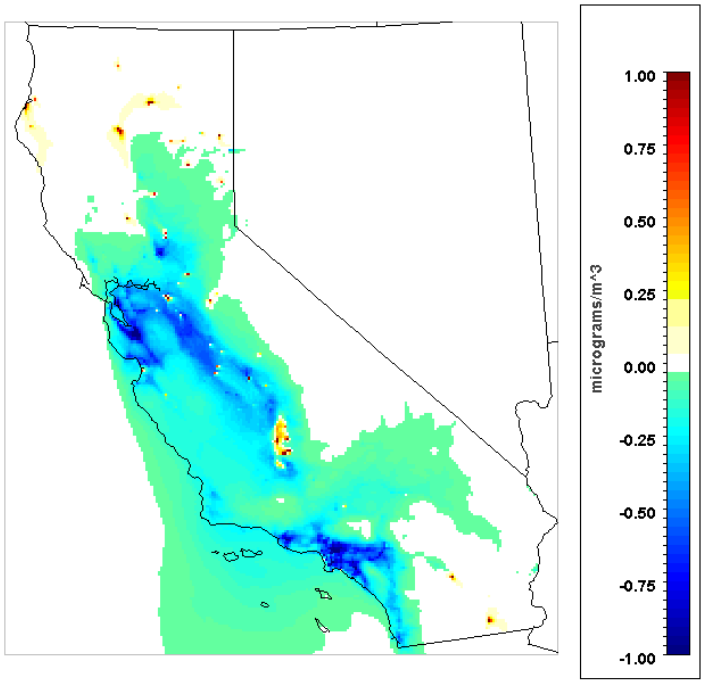


Figure 183 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResComTra2030 Case from the Base Case. Quantitatively, impacts range from -1.41 to 3.66 μg/m³and are largely beneficial to the State. Large areas of concentration reduction occur in the Bay Area, Central Valley, and SoCAB. Localized areas of worsening do occur adjacent to some generator locations.

Figure 183: Difference in 24-hour $PM_{2.5}$ in summer 2030 ResComTra Case from the Base Case



Winter

Figure 184 displays the difference in maximum 8-hour average ozone in the Winter ResComTra 2030 Case from the Base Case. Quantitatively, impacts range from -2.62 to +3.34 ppb, although generally much of the State experiences increases in ground-level concentrations.

Figure 184: Difference in maximum 8-hour ozone in winter 2030 ResComTra Case from the Base Case

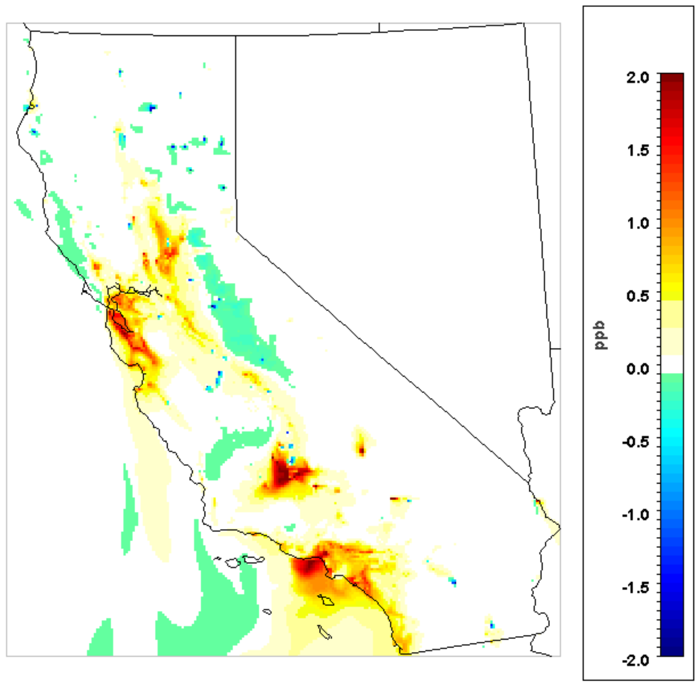
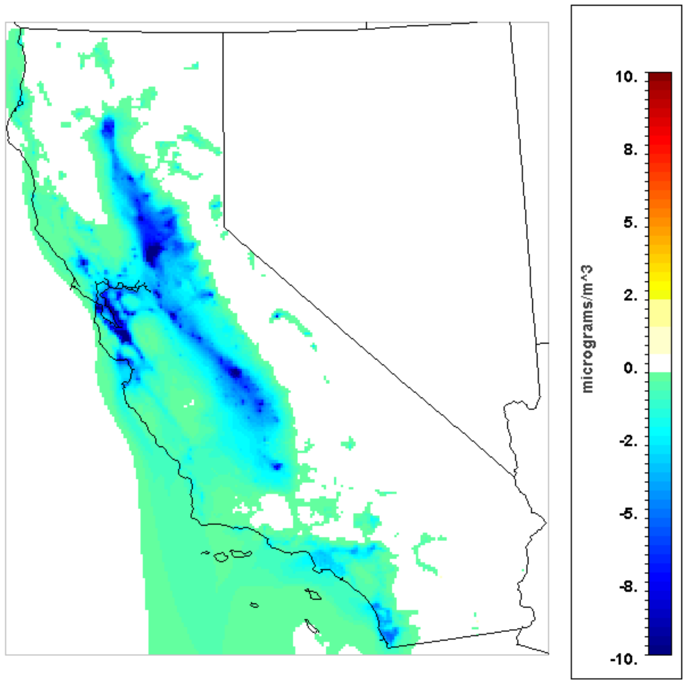


Figure 185 displays the difference in 24-hour $PM_{2.5}$ in the Winter ResComTra 2030 Case from the Base Case. Quantitatively, impacts range from -15.09 to +1.11 μg/m³. Impacts are characterized by significant improvement in ground-level concentrations throughout many regions of the State.

Figure 185: Difference in 24-hour $PM_{2.5}$ in winter 2030 ResComTra Case from the Base Case



4.4.2.9 2030 All Sectors Electrification Case (2030 ResComTraInd Case)

Summer

Figure 186 displays the difference in maximum 8-hour average ozone in the Summer ResComTraInd 2030 Case from the Base Case. Quantitatively, impacts range from -8.63 to +2.91 ppb. The impacts of the industrial sector electrification are evident in the plumes of worsening that occur mirroring the Industrial Sector Case in isolation.

Figure 186: Difference in Maximum 8-hour Ozone in summer 2030 ResComTraInd Case from the Base Case

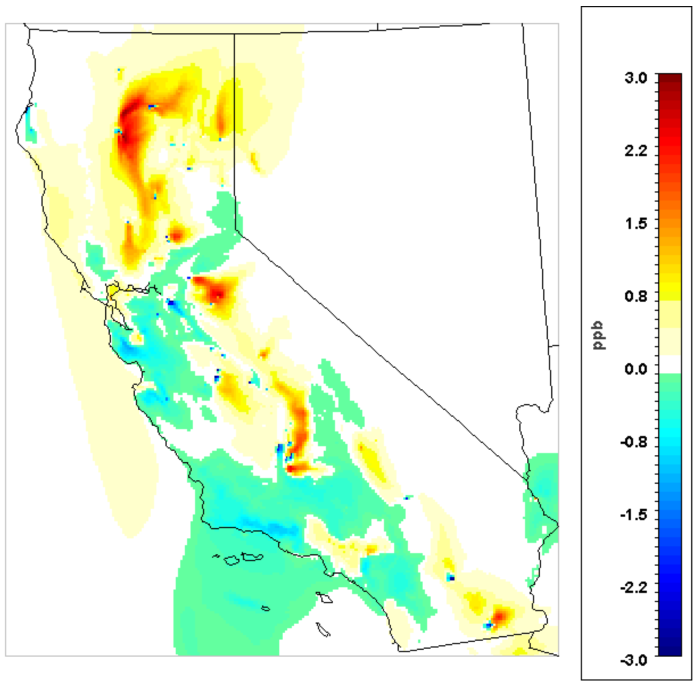
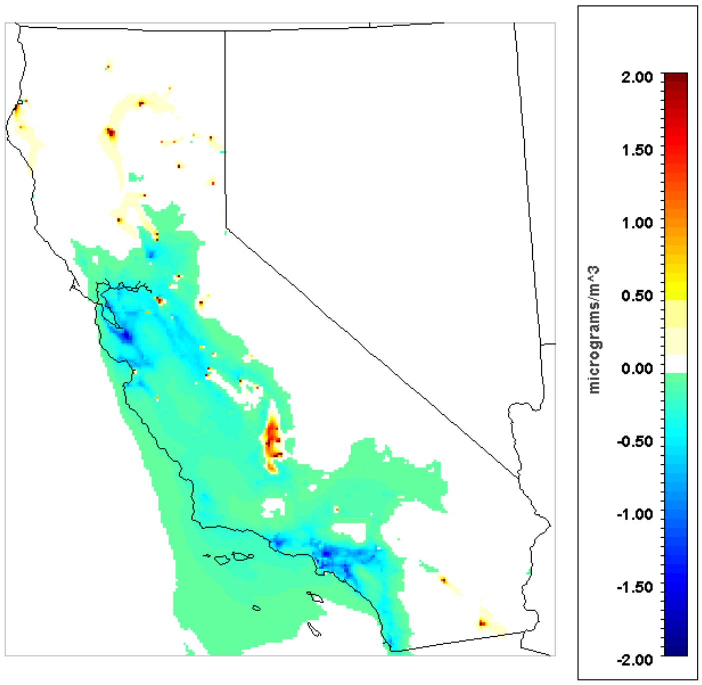


Figure 187 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResComTraInd 2030 Case from the Base Case. Quantitatively, impacts range from -1.77 to +8.60 μg/m³. Impacts are largely beneficial including improvements from emission reductions in SoCAB and the SF Bay Area. Contrastingly, increases occur from gas generator emissions in Bakersfield and some generators in Northern California.

Figure 187: Difference in 24-hour $PM_{2.5}$ in summer 2030 ResComTraInd Case from the Base Case



Winter

Figure 188 displays the difference in maximum 8-hour average ozone in the Winter ResComTraInd 2030 Case from the Base Case. Quantitatively, impacts range from -12.34 to +3.65 ppb. The majority of impacts are represented by increases in ground-level concentrations including in Bakersfield, SoCAB and the SF Bay Area.

Figure 188: Difference in Maximum 8-hour ozone in 2030 winter ResComTraInd Case from the Base Case

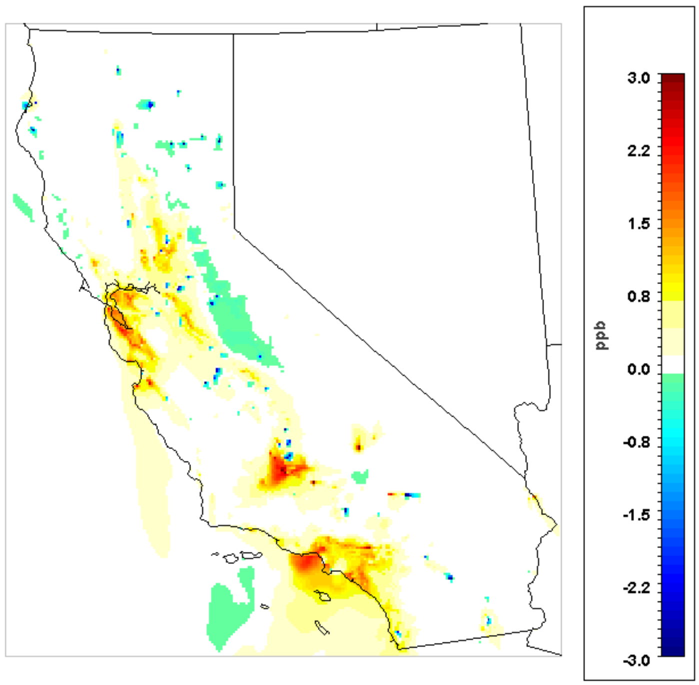
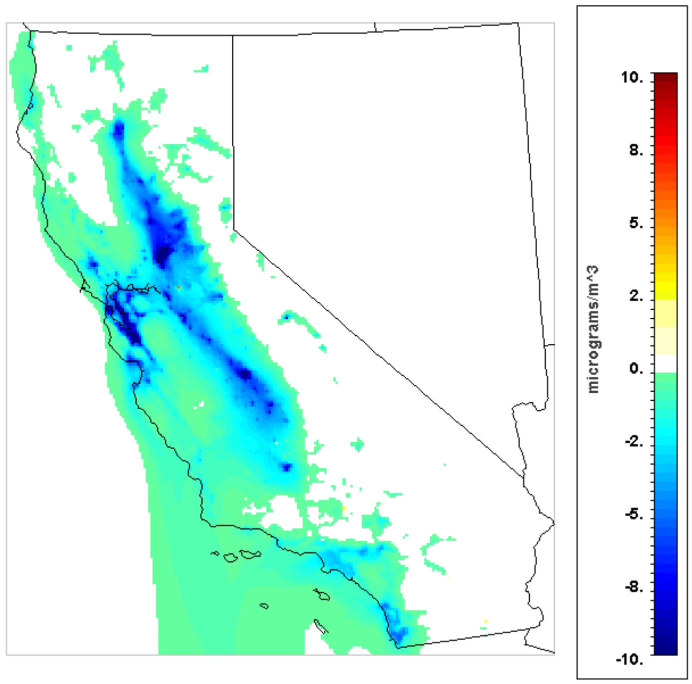


Figure 189 displays the difference in 24-hour $PM_{2.5}$ in the Winter ResComTraInd 2030 Case from the Base Case. Quantitatively, impacts range from -15.26 to +5.79 μg/m³. Impacts are almost exclusively beneficial and include dramatic improvements in the SF Bay Area, Central Valley, and SMUD regions. Reductions in emissions from winter time residential scenarios appear to contribute to the overall impacts.

Figure 189: Difference in 24-hour $PM_{2.5}$ in 2030 winter ResComTraInd Case from the Base Case



4.4.2.10 *Summary of 2030 Cases*

Table 17 displays the peak impacts on 8-hour average ozone and 24-hour $PM_{2.5}$ for the Summer 2030 Cases relative to the Base Case. Table 18 displays the peak impacts on 8-hour average ozone and 24-hour $PM_{2.5}$ for the Winter 2030 Cases relative to the Base Case. Impacts on $PM_{2.5}$ and ozone are moderate to substantial for all electrification scenarios in 2030 and reflect a higher electrification potential from 2020 for many sectors of study. Impacts on max 8-hour ozone range from -12.34 in the Winter ResComTraInd Case to +2.91 in the same Case.

Table 17: Summary of peak impacts on 8-hour max ozone and 24-hour PM2.5 for summer 2030 Cases

Summer Case	8-hour Ozone [ppb]	24-hour $PM_{2.5}$ [$\mu g/m^3$]
2030 Res	-1.33 to +0.44	-0.19 to +1.13
2030 Com	-0.96 to +1.85	-0.99 to +0.48
2030 ResCom	-2.24 to +1.93	-1.07 to +1.42
2030 Ind	-4.63 to +1.49	-0.48 to +4.34
2030 Tra	-2.41 to +0.92	-0.76 to +2.04
2030 Tra Smart	-1.89 to +0.63	-0.96 to +1.02
2030 ResComTra	-4.49 to +1.92	-1.41 to +3.66
2030 ResComTraInd	-8.63 to +2.91	-1.77 to +8.60

Table 18: Summary of peak impacts on 8-hour max ozone and 24-hour $PM_{2.5}$ for winter 2030 Cases

Winter Case	8-hour Ozone [ppb]	24-hour $PM_{2.5}$ [$\mu g/m^3$]
2030 Res	-0.78 to +1.82	-13.33 to +0.25
2030 Com	-0.49 to +3.19	-2.69 to +0.19
2030 ResCom	-3.56 to +3.31	-14.51 to +0.45
2030 Ind	-10.18 to +1.52	-1.21 to +1.29
2030 Tra	-1.63 to +0.67	-1.08 to +0.60
2030 Tra Smart	-0.81 to +0.69	-1.65 to +0.39
2030 ResComTra	-2.62 to +3.34	-15.09 to +1.11
2030 ResComTraInd	-12.34 to +3.65	-15.26 to +5.79

4.4.3 Air Quality Impacts of 2050 Scenarios

4.4.3.1 2050 Residential Electrification Case (2050 Res Case)

<u>Summer</u>

Figure 190 displays the difference in maximum 8-hour average ozone in the summer 2050 Residential Case from the Base Case. Quantitatively, impacts range from -2.12 to +1.07 ppb. Scenario results are characterized by moderate improvements in some areas of the SoCAB and Bay Area. In contrast, generator emission increases results in moderate worsening in the Central Valley and Sacramento areas.

Figure 190: Difference in Maximum 8-hour Ozone in Summer 2050 Residential Case from the Base Case

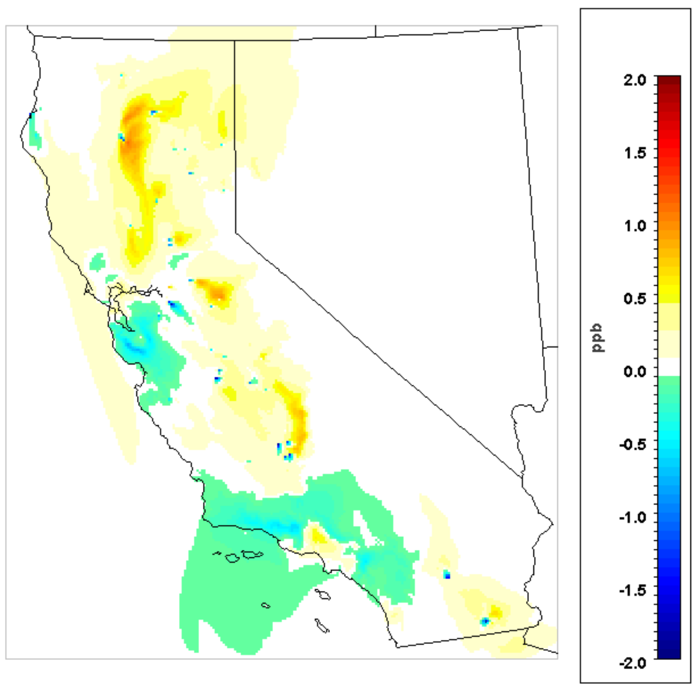
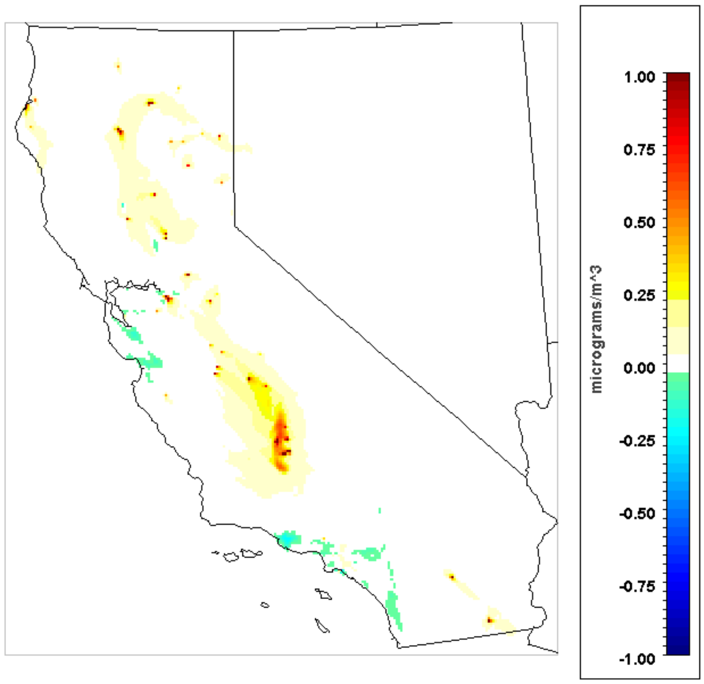


Figure 191 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2050 Residential Case from the Base Case. Quantitatively, impacts range from -1.02 to +3.37 μg/m^3. Scenario results are characterized largely by moderate worsening from several regions of the State as a result of increased generator emissions. While impacts are highly localized, magnitudes of increases are high (peak increases of 3.37 μg/m^3) and warrant some concern; especially as areas of peak worsening include the Central Valley.

Figure 191: Difference in 24-hour Average $PM_{2.5}$ in summer 2050 Residential Case from the Base Case



Winter

Figure 192 displays the difference in maximum 8-hour average ozone in the winter 2050 Residential Case from the Base Case. Quantitatively, impacts range from -10.02 to +3.64 ppb. Impacts arise from the impacts of winter ozone formation and include increases in SoCAB and the Bay Area. Moderate reductions occur in other areas of the State.

Figure 192: Difference in Maximum 8-hour Ozone in winter 2050 Residential Case from the Base Case

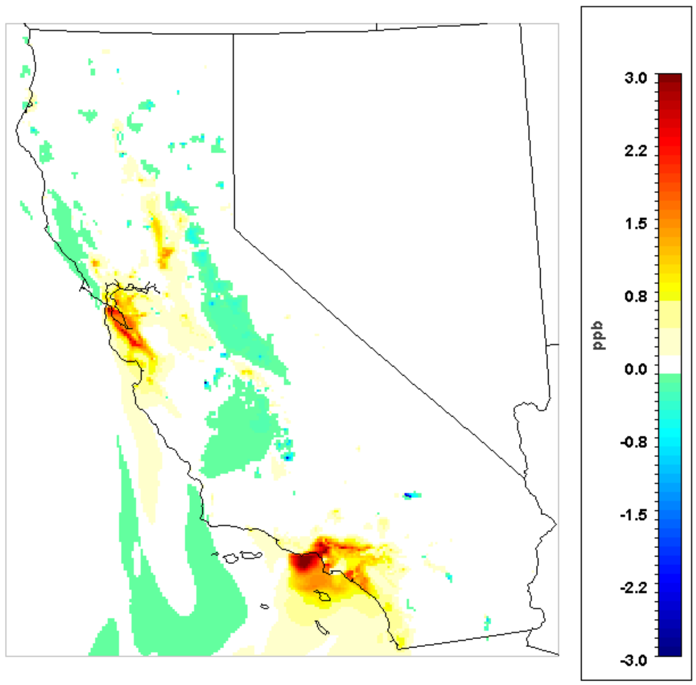
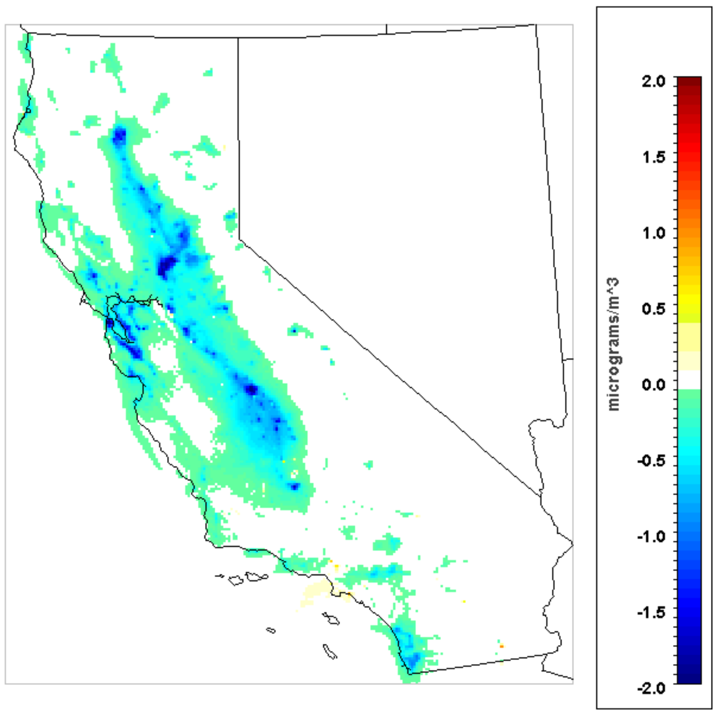


Figure 193 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2050 Residential Case from the Base Case. Quantitatively, impacts range from -3.36 to +0.96 μg/m^3. Impacts are almost solely associated with improvements in ground-level concentrations. Areas of notable improvement include the SF Bay Area, SMUD, and the Central Valley. The impacts could be associated with reductions in emissions including residential combustion of wood for heating which generates significant amounts of PM.

Figure 193: Difference in 24-hour Average $PM_{2.5}$ in winter 2050 Residential Case from the Base Case



4.4.3.2 Commercial Sector 2050 Case

<u>Summer</u>

Figure 194 displays the difference in maximum 8-hour average ozone in the Summer 2050 Commercial Case from the Base Case. Quantitatively, impacts range from -2.0 to +5.29 ppb. Impacts include significant areas of reductions in ozone levels; with peak impacts occurring in the Bay Area, Central Valley, and SoCAB. Areas of worsening also occur in the Central Valley, with a localized area near Bakersfield experiencing significant increases (+5.29 ppb). The northern portion of the State also displays some worsening due to generator emissions.

Figure 194: Difference in Maximum 8-hour Ozone in summer 2050 Commercial Case from the Base Case

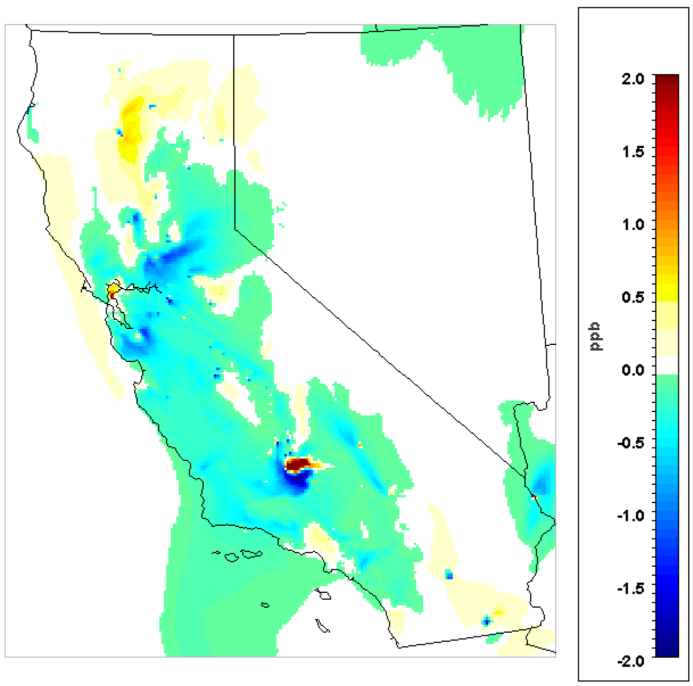
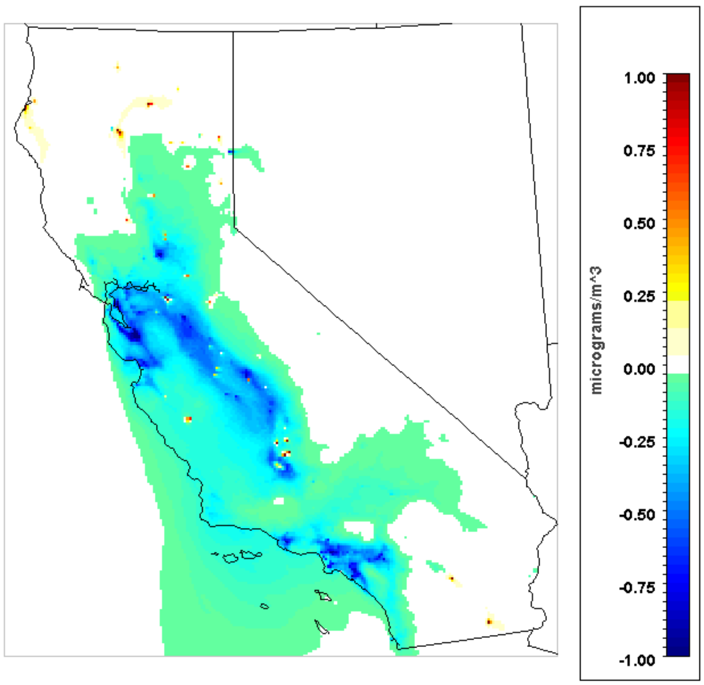


Figure 195 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2050 Commercial Case from the Base Case. Impacts range from -1.37 to +2.06 μg/m³. Impacts are largely characterized by improvements, with peak effects occurring in key areas of the State (SoCAB, the Central Valley, and the Bay Area). Some localized worsening occurs at sites of fossil fuel generators, however overall impacts are largely beneficial.

Figure 195: Difference in 24-hour Average $PM_{2.5}$ in summer 2050 Commercial Case from the Base Case



Winter

Figure 196 displays the difference in maximum 8-hour average ozone in the Winter 2050 Commercial Case from the Base Case. Quantitatively, impacts range from -1.60 to +7.27 ppb. Impacts are largely described by increases in ground-level ozone concentrations across the State. The winter time dynamics associated with ozone formation and fate result in increases in areas that experience NO_x reductions.

Figure 196: Difference in Maximum 8-hour Ozone in winter 2050 Commercial Case from the Base Case

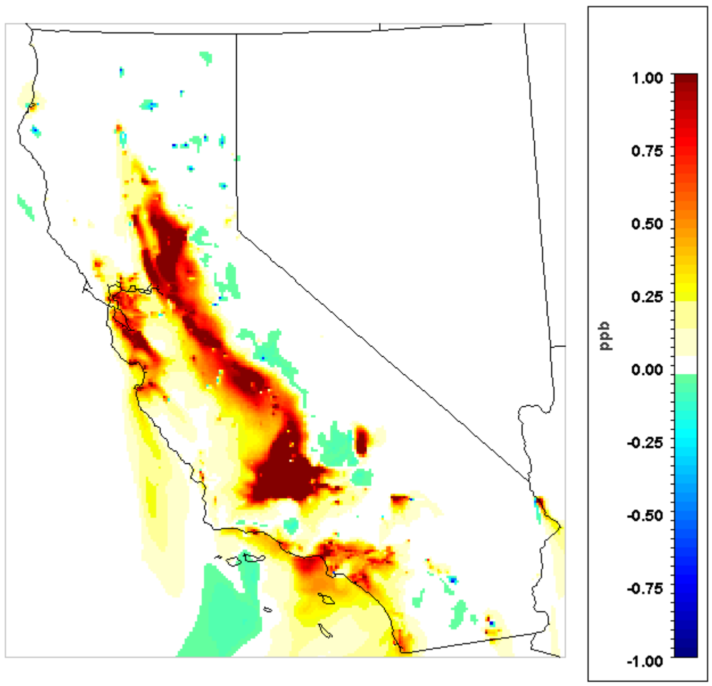
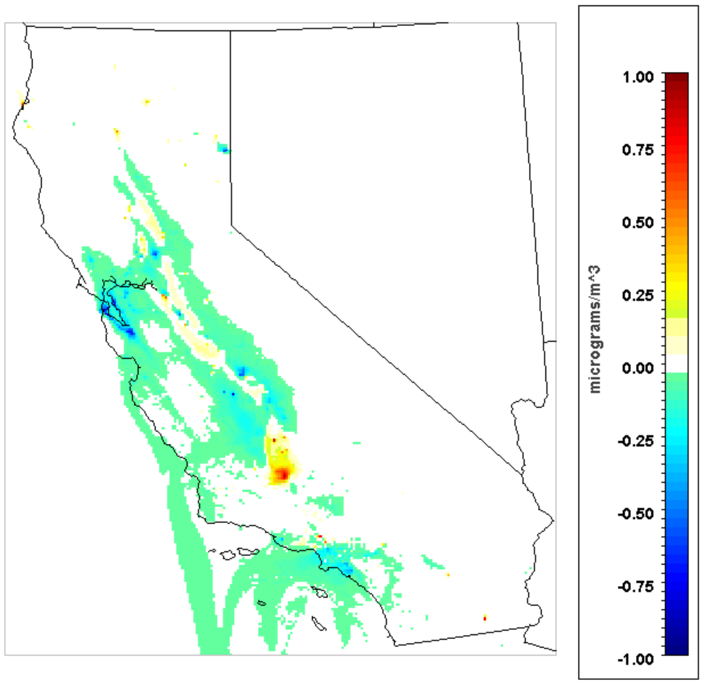


Figure 197 displays the difference in 24-hour $PM_{2.5}$ in the winter 2050 Commercial Case from the Base Case. Quantitatively, impacts range from -1.64 to +0.87 μg/m^3. Generally, impacts are fairly moderate with peak worsening occurring in the Bakersfield due to increased gas generator emissions. Contrastingly, improvements occur in other areas of the State including SoCAB and the SF Bay Area.

Figure 197: Difference in 24-hour Average $PM_{2.5}$ in winter 2050 Commercial Case from the Base Case



4.4.3.3 2050 Residential and Commercial Electrification Case (2050 ResCom Case)

Summer

Figure 198 displays the difference in maximum 8-hour average ozone in the Summer ResCom 2050 Case from the Base Case. Impacts range in magnitude from -3.83 to +5.48 ppb. NO_x increases from generators result in notable areas of worsening in Bakersfield and, to a lesser degree, northern areas of the State. Reductions in NO_x from residential and commercial sectors yield improvements in many others regions of the State including SoCAB and the SF Bay Area.

Figure 198: Difference in Maximum 8-hour Average Ozone in the Summer ResCom 2050 Case from the Base Case

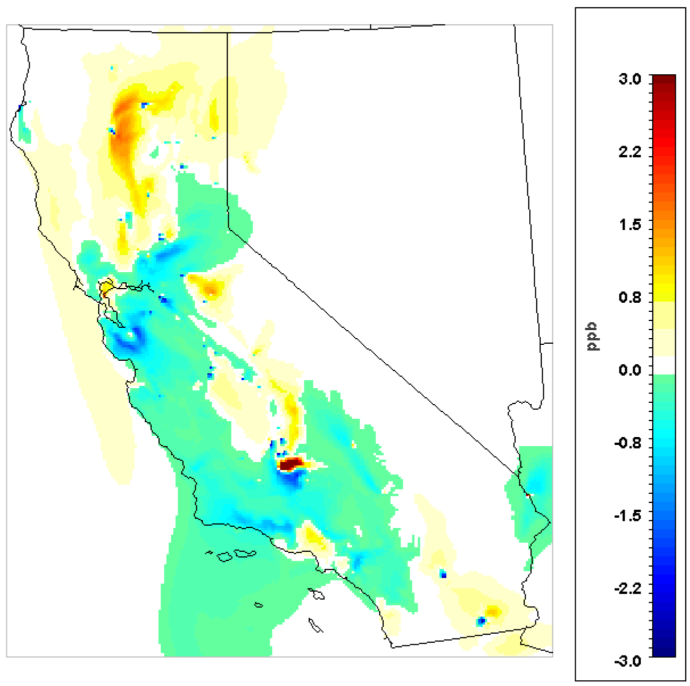
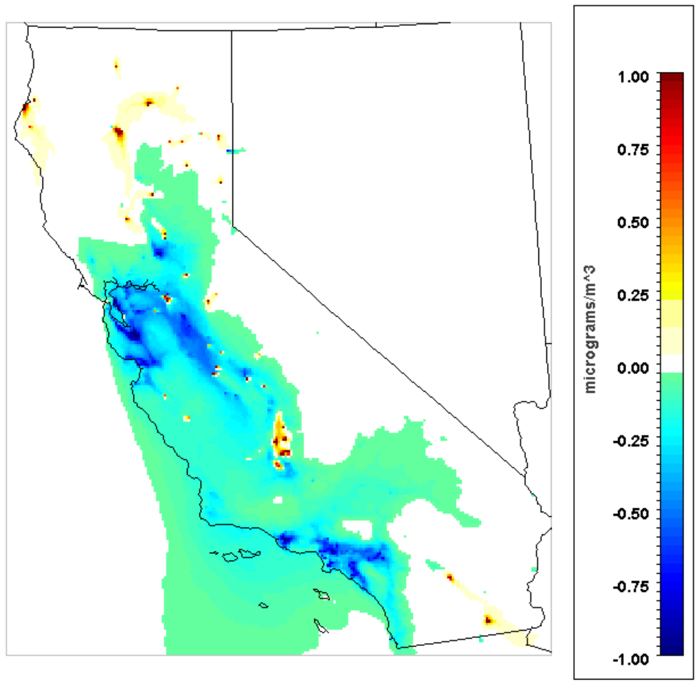


Figure 199 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResCom 2050 Case from the Base Case. Quantitatively, impacts range from -1.41 to +5.61 μg/m³ and represent an additive outcome relative to the individual cases. Largely, reductions occur over large areas of the State with peak impacts in the SF Bay Area and SoCAB.

Figure 199: Difference in 24-hour Average $PM_{2.5}$ in the Summer ResCom 2050 Case from the Base Case



Winter

Figure 200 displays the difference in maximum 8-hour average ozone in the Winter ResCom 2050 Case from the Base Case. Quantitatively, impacts range from -13.45 to +7.46 ppb. In general, impacts are moderate to minor and result from the winter-time ozone formation dynamics.

Figure 200: Difference in Maximum 8-hour Average Ozone in the Winter ResCom 2050 Case from the Base Case

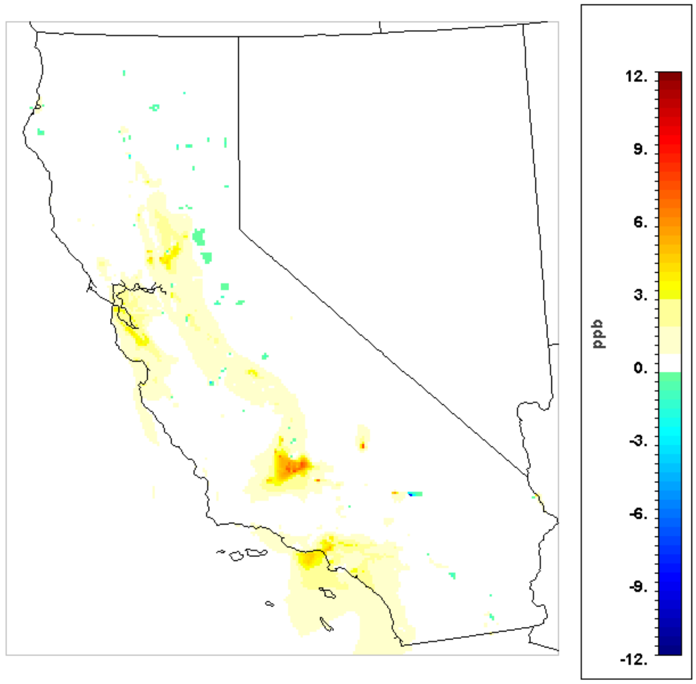
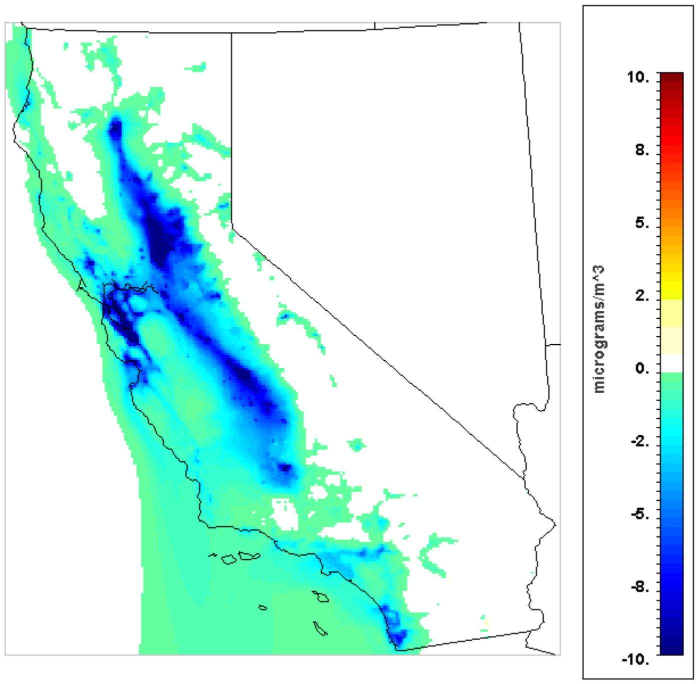


Figure 201 displays the difference in 24-hour $PM_{2.5}$ in the Winter ResCom 2050 Case from the Base Case. Quantitatively, impacts range from -20.62 to +1.77 μg/m³. Impacts are highly beneficial and include large reductions throughout the State. The largest benefits occur in the SF Bay Area and northern portion of the Central Valley.

Figure 201: Difference in 24-hour Average $PM_{2.5}$ in the Winter ResCom 2050 Case from the Base Case



4.4.3.4 2050 Industrial Electrification Sector Case (2050 Ind case)

Summer

Figure 202 displays the difference in maximum 8-hour average ozone in the Summer 2050 Industrial Case from the Base Case. Quantitatively, impacts range from -7.10 to +3.58 ppb. Impacts from electrification of industrial sources largely include significant worsening across the Central Valley and northern regions of the State from increased NO_x emissions from generators. Additionally, areas of localized worsening occur in the southern portion adjacent to the border with Mexico. Areas of improvement are lesser in magnitude and include some areas of SoCAB and Bakersfield as a result of reduced NO_x from large industrial sources. Additionally, one site near the Bay Area experiences a plume of reduction with high magnitude. However, impacts on ozone are generally deletorious for the scenario and demonstrate the high increase in electricity needed to meet sector electrification needs as a result of the replacement of efficient technologies.

Figure 202: Difference in Maximum 8-hour Average Ozone in the Summer 2050 Industrial Case from the Base Case

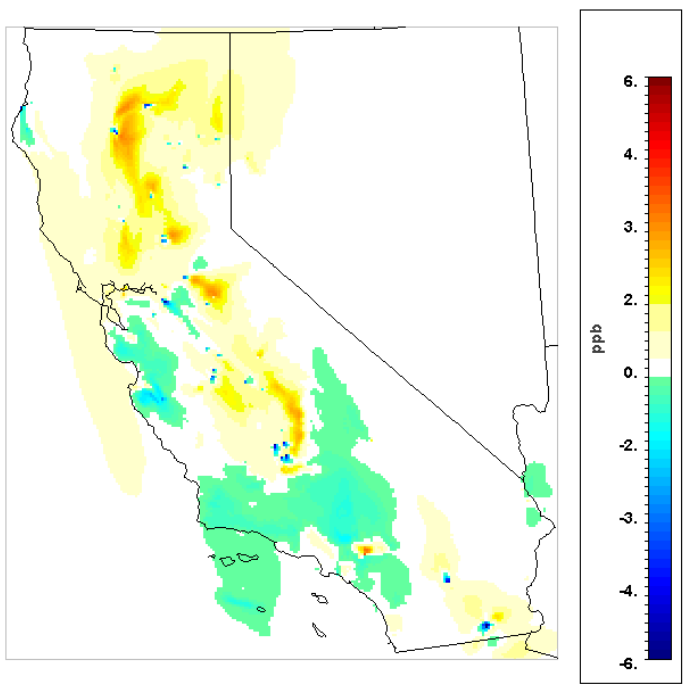
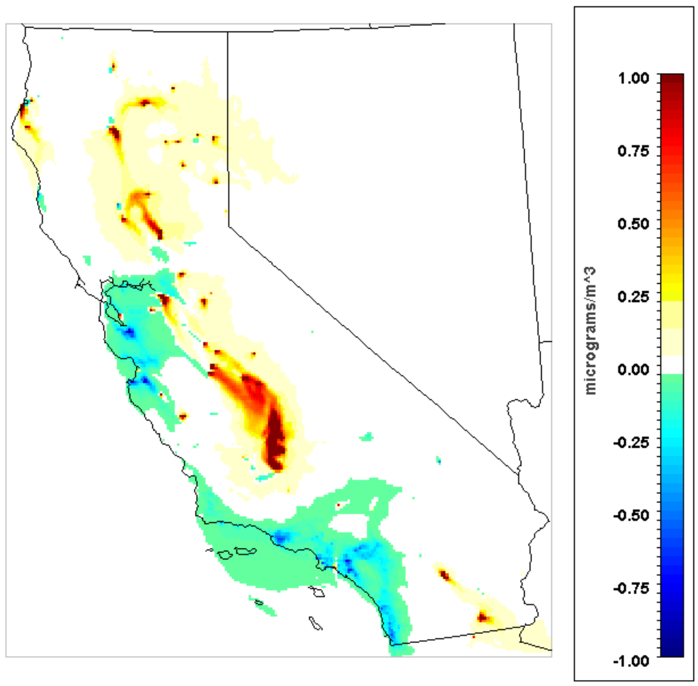


Figure 203 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2050 Industrial Case from the Base Case. Quantitatively, impacts range from -1.10 to +12.40 μg/m³. Impacts for $PM_{2.5}$ are similar to those for ozone in that increases in ground level concentrations are the dominant effect, including in the Central Valley and northern part of the State. Additionally, improvements are observed in the Bay Area and SoCAB although at a lesser magnitude.

Figure 203: Difference in 24-hour Average $PM_{2.5}$ in the Summer 2050 Industrial Case from the Base Case



Winter

Figure 204 displays the difference in maximum 8-hour average ozone in the Winter 2050 Industrial Case from the Base Case. Quantitatively, impacts range from -13.61 to +5.55 ppb. Impacts largely include worsening of ground-level concentrations including peak impacts in SoCAB due to the inverse NO_x relationship observed in winter. Generally, impacts are fairly minor in spatial coverage relative to other cases.

Figure 204: Difference in Maximum 8-hour Average Ozone in the Winter 2050 Industrial Case from the Base Case

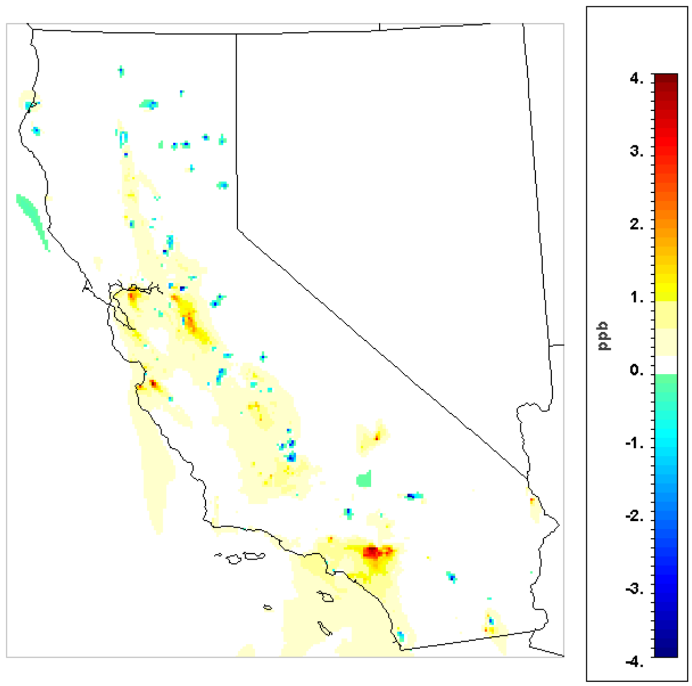
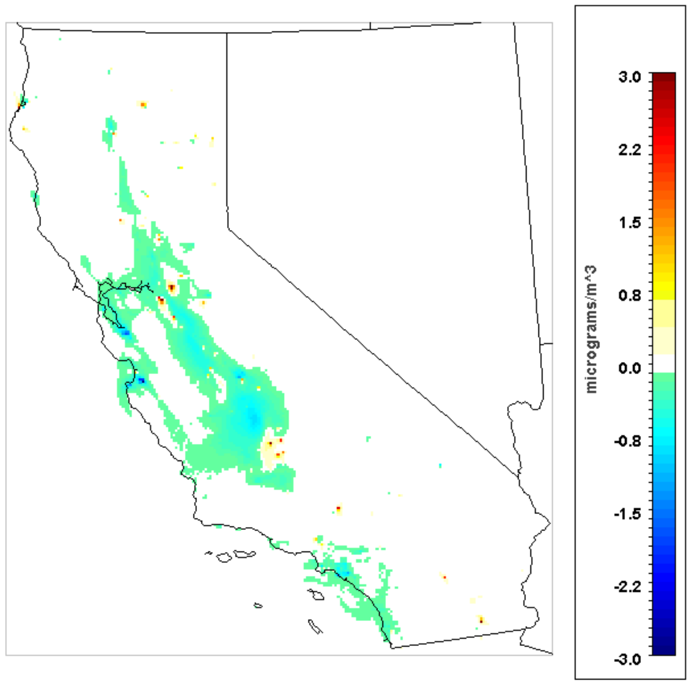


Figure 205 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2050 Industrial Case from the Base Case. Quantitatively, impacts range from -3.22 to +12.28 µg/m^3. Overall, impacts are fairly minor for both reductions and increases. As can be seen, impacts tend to be localized with the largest area of improvement occurring in the SF Bay Area and Central Valley. Some improvement is also seen from NO_x reductions in SoCAB. Contrastingly some localized worsening occurs, notable from the Bakersfield area gas generators.

Figure 205: Difference in 24-hour Average PM2.5 in the Winter 2050 Industrial Case from the Base Case



4.4.3.5 2050 Immediate Transportation Electrification Case (2050 Immediate Tra Case)

Summer

Figure 206 displays the difference in maximum 8-hour average ozone in the Summer 2050 Transportation Case from the Base Case. Quantitatively, impacts range from -2.61 to +1.69 ppb. Spatially, impacts on ozone include improvements in the Bay Area and SoCAB and worsening seen in plumes in the Central Valley and across the northern parts of the State. As would be expected, reductions occur as a result of reduced NO_x from vehicle tailpipes and petroleum fuel refineries while increases result from additional generator NO_x. However, the magnitude of peak reductions is greater than concentrations increases and covers a larger spatial area. Additionally, it should be considered that the improvements occur in large urban areas with high populations as a result of concentrated vehicle presence and thus are important in terms of health impacts. Contrastingly, much of the worsening occurs in the northern regions of the State with lower population density. Thus, the results from this scenario would generally be viewed as an air quality benefit to the State, although additional strategies to limit the increase in generator NO_x from the Bakersfield-area plants should be pursued.

Figure 206: Difference in Maximum 8-hour Average Ozone in the summer 2050 Immediate Transportation Case from the Base Case

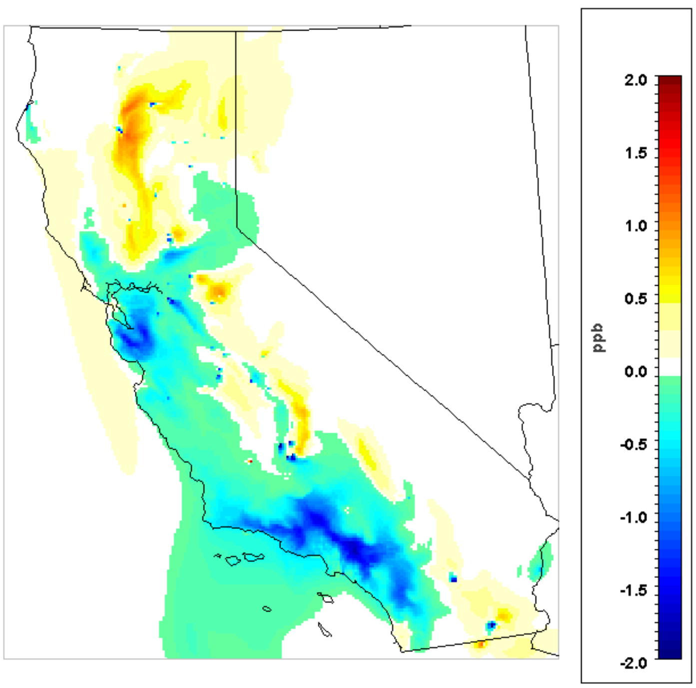
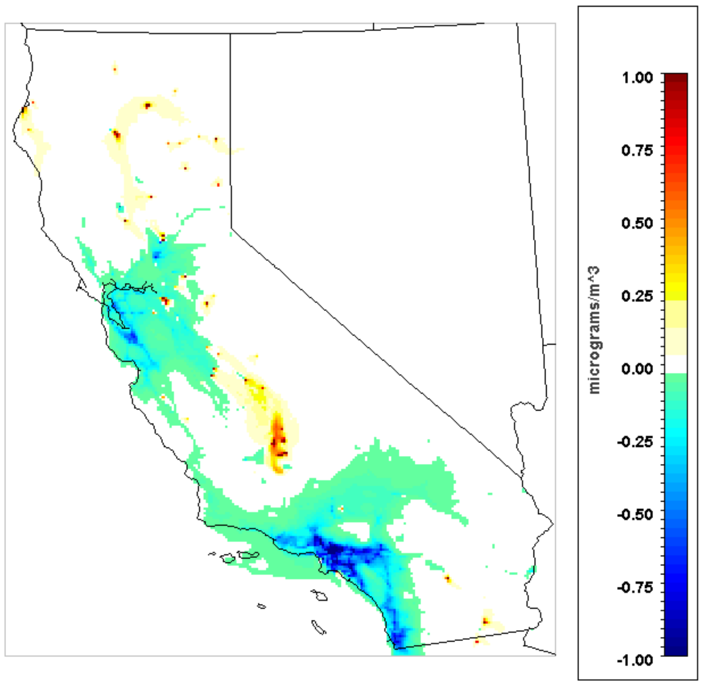


Figure 207 displays the difference in 24-hour $PM_{2.5}$ in the Summer 2050 Transportation Case from the Base Case. Quantitatively, impacts range from -1.85 to +3.98 μg/m^3 and are similar in spatial effect to those observed for ozone. Notable improvements occur in the SoCAB and the Bay Area while worsening occurs in the Central Valley and northern region.

Figure 207: Difference in 24-hour Average $PM_{2.5}$ in the summer 2050 Immediate Transportation Case from the Base Case



Winter

Figure 208 displays the difference in maximum 8-hour average ozone in the Winter 2050 Transportation Case from the Base Case. Quantitatively, impacts range from -30.28 to +12.86 ppb. Impacts are significant, both in magnitude and in spatial coverage and largely are characterized by reductions in ground level concentrations. Areas of improvement include SoCAB, Central Valley, and the Bay Area. The wintertime dynamics of ozone raise questions however as relationships are generally inverse to NO_x emissions which is not observed in this scenario.

Figure 208: Difference in Maximum 8-hour Average Ozone in winter 2050 Immediate Transportation Case from the Base Case

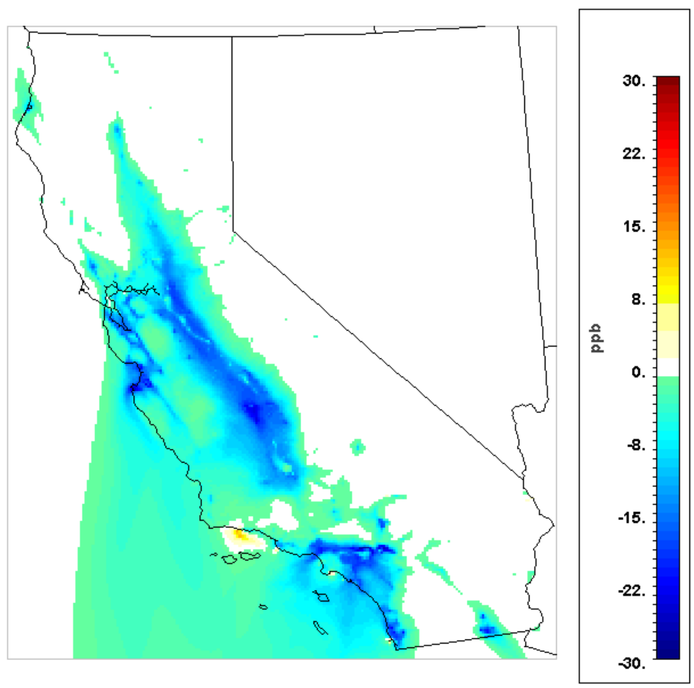
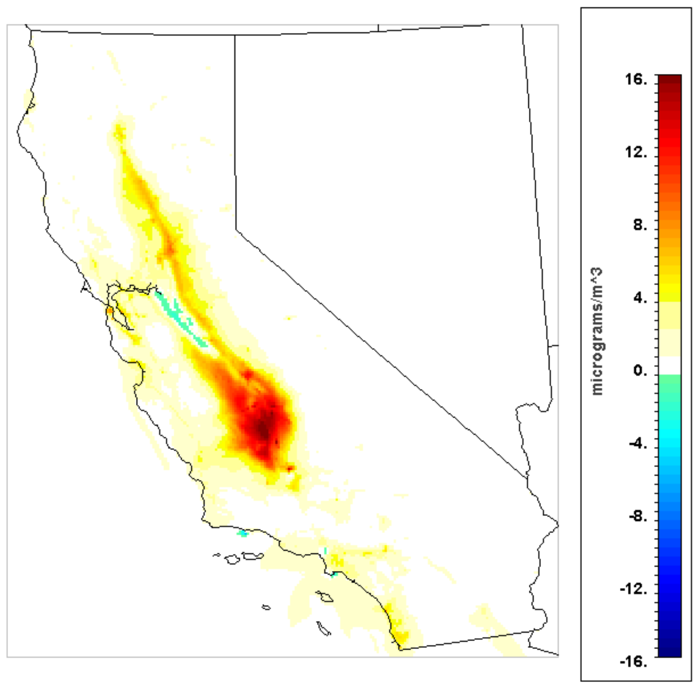


Figure 209 displays the difference in 24-hour $PM_{2.5}$ in the Winter 2050 Transportation Case from the Base Case. Quantitatively, impacts range from -5.89 to +16.32 μg/m³. The relative lack of PM emissions from LDV tailpipe generally results in worsening as increased generator emissions dominate total impacts. The central valley experiences a major area of worsening which is a concern due to existing air quality challenges – particularly winter PM levels.

Figure 209: Difference in 24-hour Average $PM_{2.5}$ in the winter 2050 Immediate Transportation Case from the Base Case



4.4.3.6 2050 Smart Transportation Electrification Case (2050 Smart Tra Case)

<u>Summer</u>

Figure 210 displays the difference in maximum 8-hour average ozone in the Summer Tra Smart Charging 2050 Case from the Base Case. Quantitatively, impacts range from -2.55 to +1.53 ppb. Significant reductions in ground level concentrations are observable across many regions of the Sate including SoCAB, the SF Bay Area, and much of the Central Valley. One notable area of concentration increase occurs in the northern portion of the state. However, overall impacts on ozone are favorable as improvements occur in many urban regions and would thus offer important health benefits.

Figure 210: Difference in Maximum 8-hour Average Ozone in the summer 2050 Smart Transportation Case from the Base Case

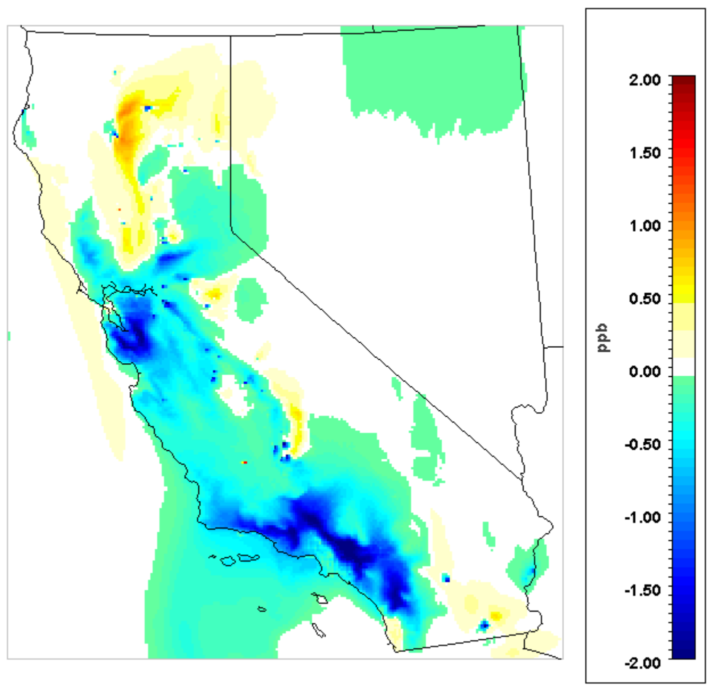
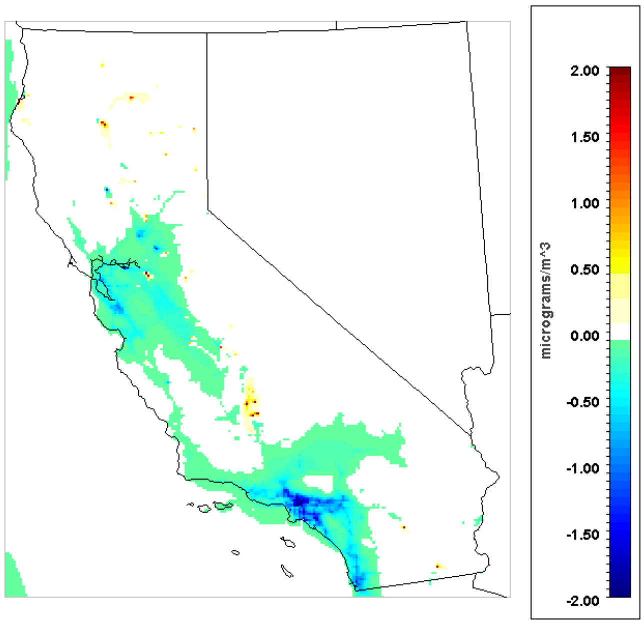


Figure 211 displays the difference in 24-hour $PM_{2.5}$ in the Summer Transportation Smart Charging 2050 Case from the Base Case. Quantitatively, impacts range from -4.17 to +3.61 µg/m^3. Impacts are largely characterized by improvements in the SoCAB and the SF Bay Area. In particular, reductions in the SoCAB represent the largest impact in the Case. Small, localized increases occur in the same location as ozone increases but are dominated by improvements.

Figure 211: Difference in 24-hour $PM_{2.5}$ in the summer 2050 Smart Transportation Case from the Base Case



Winter

Figure 212 displays the difference in maximum 8-hour average ozone in the Winter Transportation Smart Charging 2050 Case from the Base Case. Quantitatively, impacts range from -1.15 to +2.26 ppb. Spatially, impacts include areas of worsening in the SoCAB, Bay Area, and Sacramento. Areas of improvement include in and around Bakersfield. However, the winter time ozone impacts are less of a concern due to seasonal differences discussed in the results section regarding the 2020 Winter scenarios.

Figure 212: Difference in Maximum 8-hour Average Ozone in the winter 2050 Smart Transportation Case from the Base Case

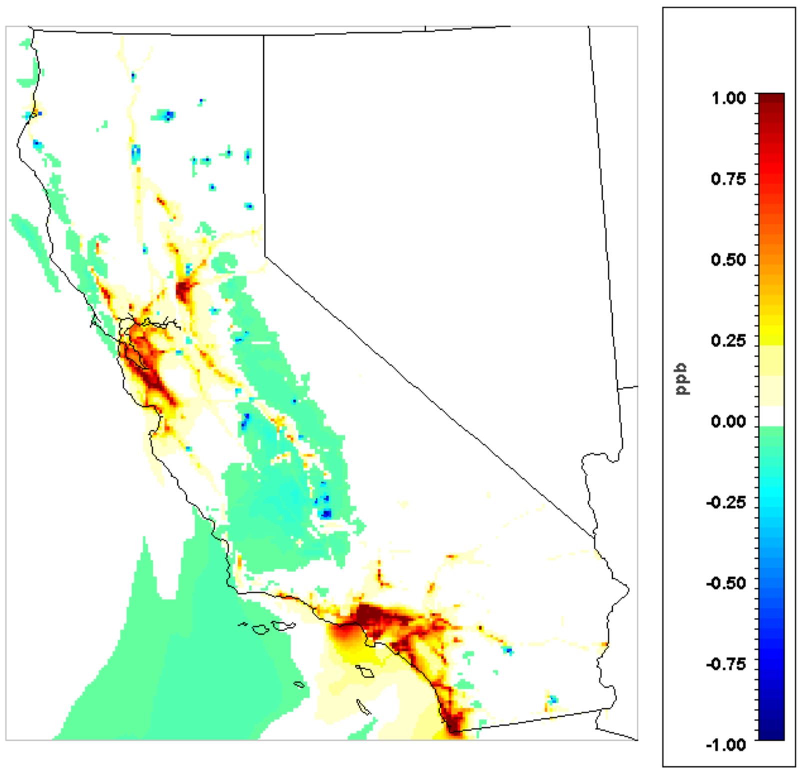
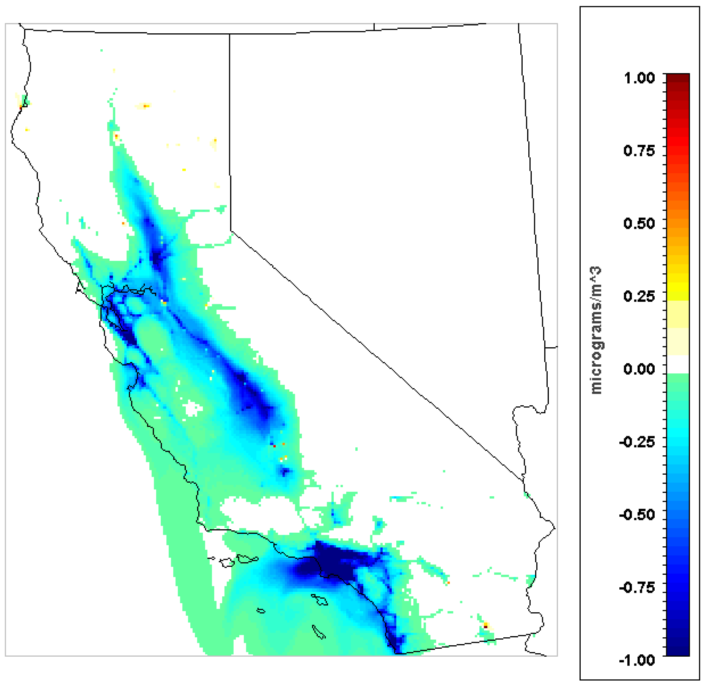


Figure 213 displays the difference in 24-hour $PM_{2.5}$ in the Winter Transportation Smart Charging 2050 Case from the Base Case. Quantitatively, impacts range from -3.16 to +1.13 μg/m^3. The magnitude of improvements are substantial and occur in important areas for winter time PM levels including the SoCAB, Central Valley, SF Bay Area, and Sacramento Area. Additionally, increases in concentrations are minor to reductions and thus not visible at the given scale. Thus, the Winter Smart Charging 2050 Transportation Case achieves important benefits to AQ in 2050.

Figure 213: Difference in 24-hour $PM_{2.5}$ in the winter 2050 Smart Transportation Case from the Base Case



4.4.3.7 Comparison of 2050 Immediate and Smart Charging Air Quality Impacts

To assess the air quality impacts of smart relative to immediate charging difference plots were generated for the Transportation Smart Charging 2050 Case relative to the 2050 Transportation Case, which assumes immediate charging of vehicles. Thus, the following figures display spatial and temporal distributions of pollutants such that negative values represent enhanced reductions and positive values represent increased concentrations when smart charging is deployed.

<u>Summer</u>

Transitioning to smart charging of electric vehicles significantly improves ozone concentrations relative to immediate charging, although this is somewhat expected given the higher EV penetration and reduction in LDV emissions. Figure 214 shows the difference in maximum 8-hour ozone from smart charging for the Summer 2050 Transportation Case. Quantitatively, impacts range from -1.05 to +0.71 ppb. The peak reductions are particularly significant given that the peak reduction of the Summer Tra2050 Case is -2.61 ppb. Peak improvements occur in many part of the State including SoCAB, SF Bay Area, and Central Valley. Evident are reductions from increased vehicle levels leading to reductions in direct emissions and reductions in emissions from power plants from the avoidance of ramping. Thus, the smart charging of vehicles can achieve important improvements in AQ benefits relative to immediate charging in terms of summer ozone levels in 2050.

Figure 214: Difference in Maximum 8-hour Ozone between the Smart and Immediate Charging Summer 2050 Transportation Cases

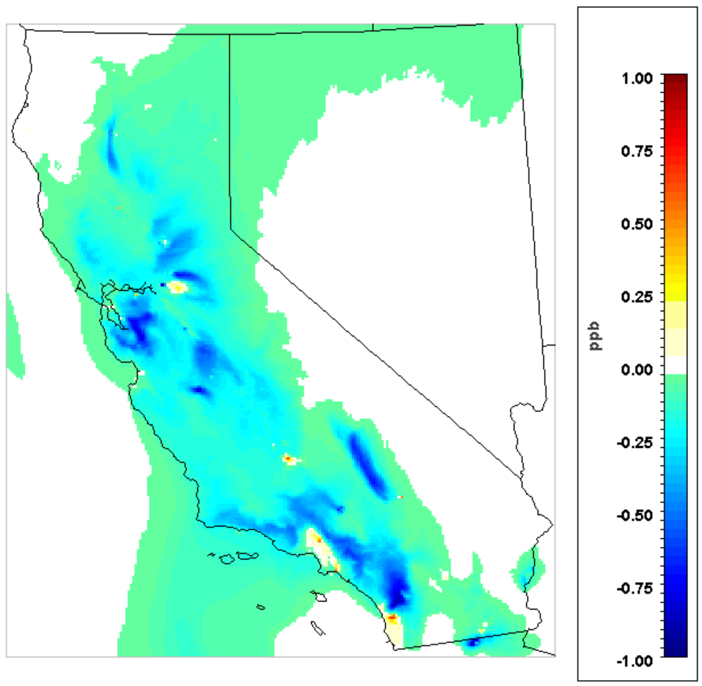
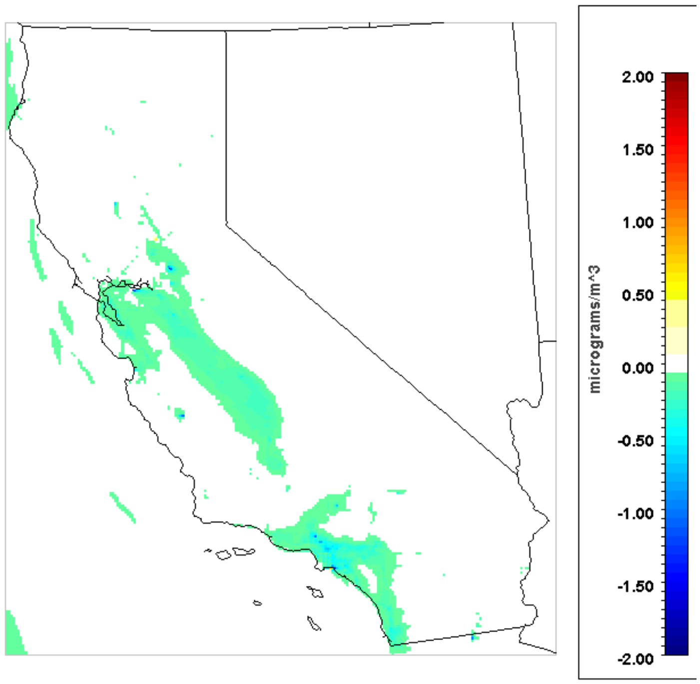


Figure 215 shows the difference in 24-hour $PM_{2.5}$ from smart charging for the Summer 2050 Transportation Case. Quantitatively, impacts range from -5.13 to +0.59 μg/m^3. With similarity to the ozone difference, impacts are characterized by improvements in many areas of the State including the SoCAB, Central Valley, and SF Bay Area. While peak reductions reach high levels, the majority of impacts are lesser. Still, a transition to smart charging achieves notable improvements in summer $PM_{2.5}$ levels from reductions in vehicle and power plant emissions.

Figure 215: Difference in 24-hour $PM_{2.5}$ between the Smart and Immediate Charging Summer 2050 Transportation Cases



Winter

Figure 216 shows the difference in maximum 8-hour ozone from smart charging for the Winter 2050 Transportation Case. Quantitatively, impacts range from -14.53 to +29.59 ppb. Impacts are largely characterized by significant increases throughout the State. Despite increases, the winter ozone dynamics limit the importance of the effects.

Figure 216: Difference in Maximum 8-hour Ozone between the Smart and Immediate Charging Winter 2050 Transportation Cases

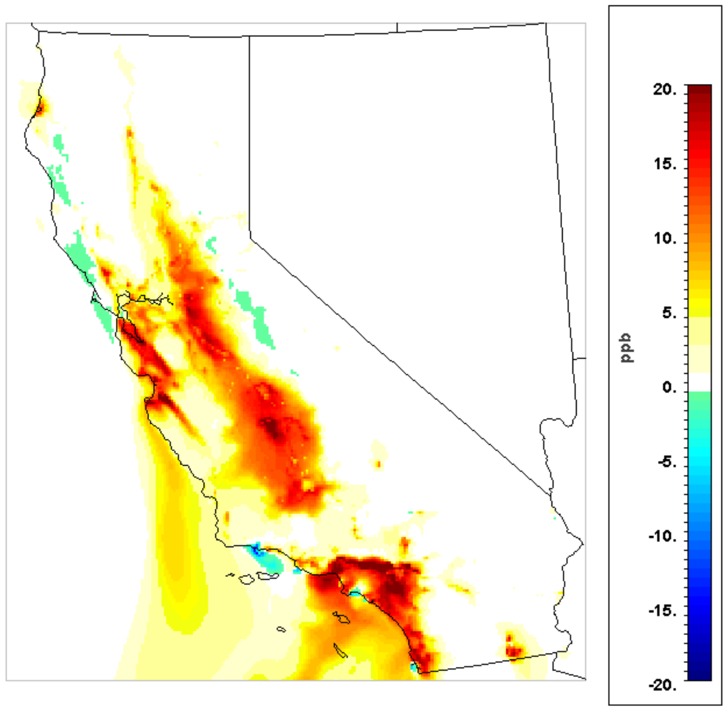
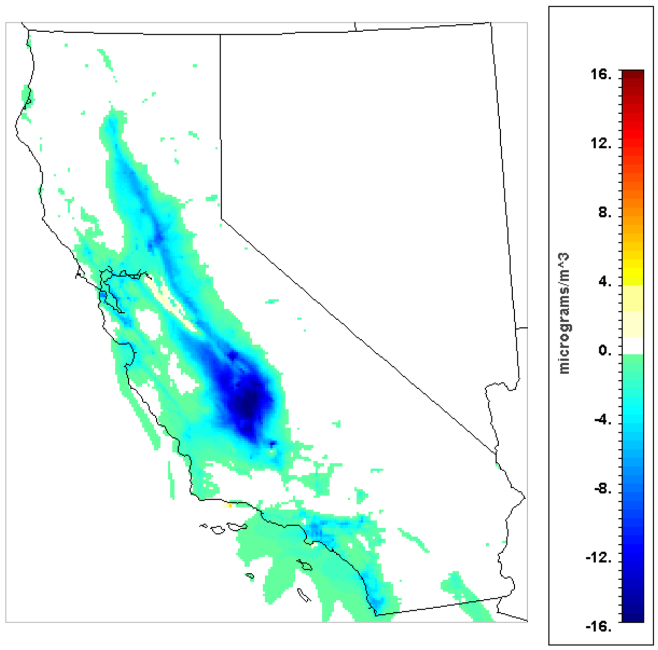


Figure 217 shows the difference in 24-hour $PM_{2.5}$ from smart charging for the Winter 2050 Transportation Case. Quantitatively, impacts range from -17.31 to +5.78 μg/m³. Impacts are largely characterized by dramatic improvements in several key areas of the State. The largest area of reduction is concentrated in the Central Valley and extends northward through Sacramento. The magnitude of the difference is particularly large.

Figure 217: Difference in 24-hour $PM_{2.5}$ between the Smart and Immediate Charging Winter 2050 Transportation Cases



4.4.3.8 2050 All Sectors Electrification Case (2050 ResComTra 2050 Case)

<u>Summer</u>

Figure 218 displays the difference in maximum 8-hour average ozone in the Summer ResComTra 2050 Case from the Base Case. Quantitatively, impacts range from -3.78 to +4.76 ppb. Results are generally additive and are characterized by large areas of improvement throughout the State. One notable area of worsening occur over Bakersfield as a result of increased NO_x from large gas generators located in the region. However, overall impacts are generally favorable.

Figure 218: Difference in Maximum 8-hour Average Ozone in the Summer ResComTra 2050 Case from the Base Case

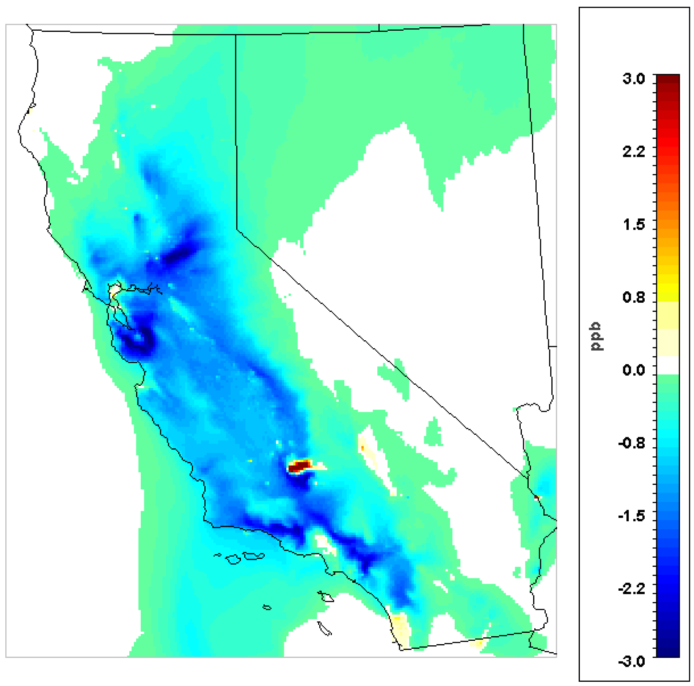
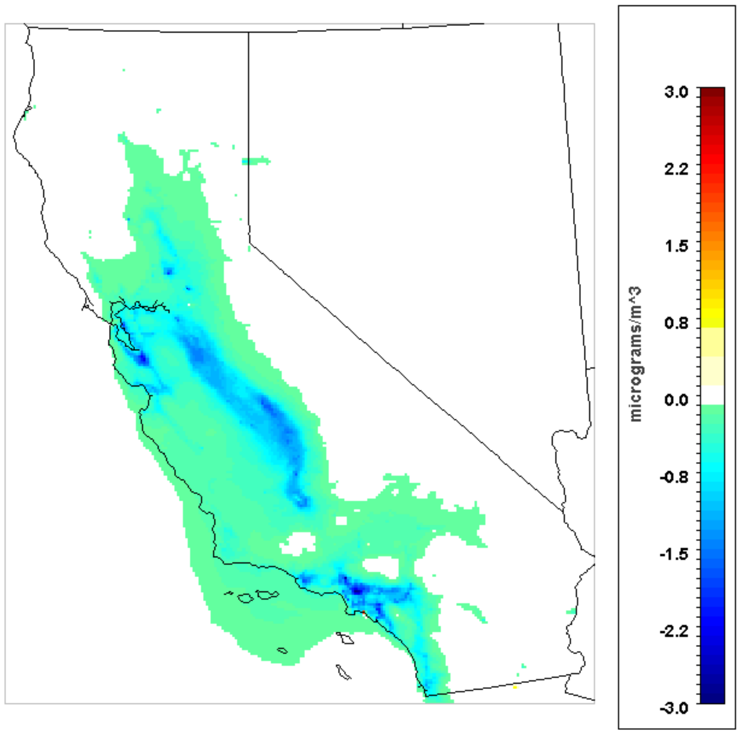


Figure 219 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResComTra 2050 Case from the Base Case. Quantitatively, impacts range from -3.82 to +1.79 μg/m³. Impacts are largely characterized by improvements throughout the State including SoCAB, the SF Bay Area, and the Central Valley, and the case represents an opportunity to improve summer air quality in terms of $PM_{2.5}$.

Figure 219: Difference in 24-hour Average $PM_{2.5}$ in the Summer ResComTra 2050 Case from the Base Case



Winter

Figure 220 displays the difference in maximum 8-hour average ozone in the Winter ResComTra 2050 Case from the Base Case. Quantitatively, impacts range from -14.13 to +31.69 ppb.

Figure 220: Difference in Maximum 8-hour Average Ozone in the Winter ResComTra 2050 Case from the Base Case

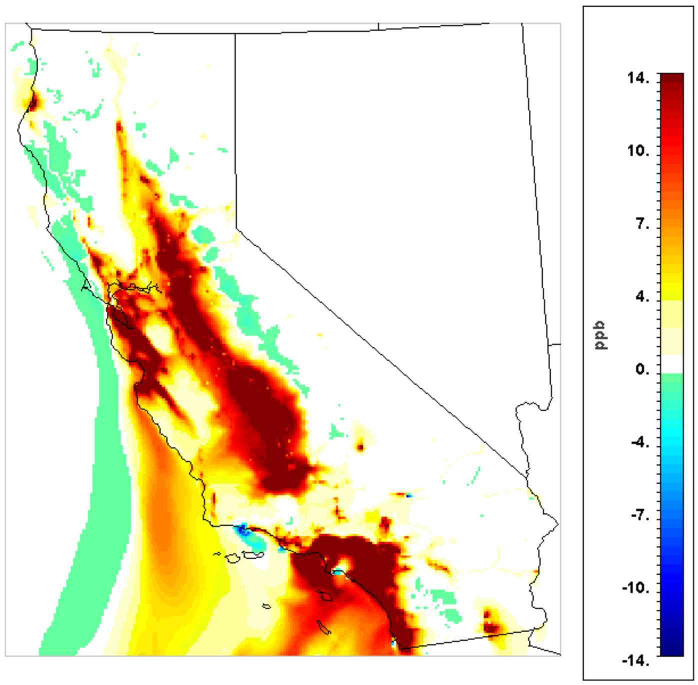
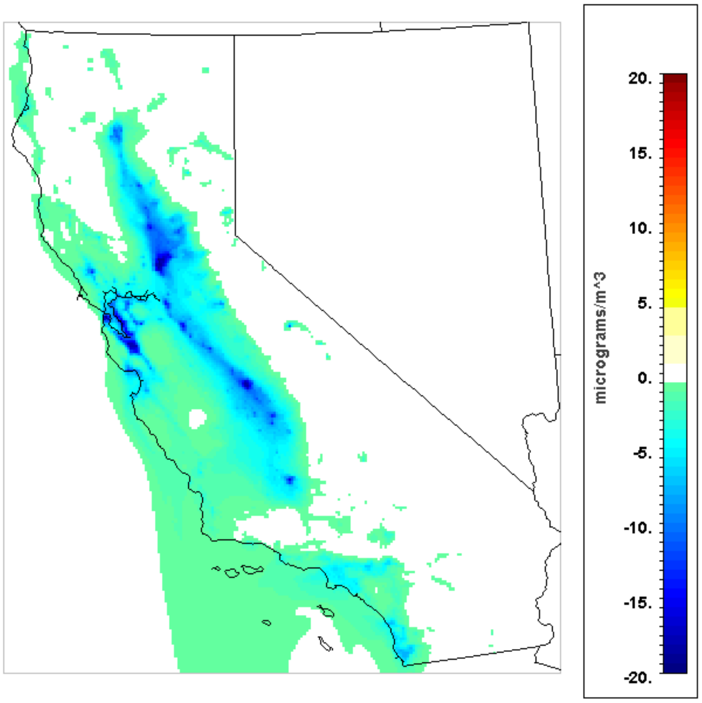


Figure 221 displays the difference in 24-hour $PM_{2.5}$ in the Summer ResComTra 2050 Case from the Base Case. Quantitatively, impacts range from -22.34 to +0.20 μg/m³.

Figure 221: Difference in 24-hour $PM_{2.5}$ in the Summer ResComTra 2050 Case from the Base Case



4.4.3.9 Summary of 2050 Cases

Table 19 displays the peak impacts on 8-hour average ozone and 24-hour $PM_{2.5}$ for the summer 2050 Cases relative to the Base Case. Table 20 displays the peak impacts on 8-hour average ozone and 24-hour $PM_{2.5}$ for the winter 2050 Cases relative to the Base Case. Impacts on $PM_{2.5}$ and ozone are substantial for all electrification scenarios in 2050 and reflect a very high electrification and renewable penetration for the sectors of study. Impacts on max 8-hour ozone range from -30.28 in the Winter Tra Case to +12.86 in the same case.

The winter episode ozone simulations result in significantly large perturbations to ground level concentrations—for example, -14.13 to +31.69 ppb in the ResComTra 2050 Case. These values are higher than what would be expected.

Table 19: Summary of peak impacts on 8-hour max ozone and 24-hour $PM_{2.5}$ for summer 2050 Cases

Summer Case	**8-hour Ozone [ppb]**	**24-hour $PM_{2.5}$ [$\mu g/m^3$]**
2050 Res	-2.12 to +1.07	-1.02 to +3.37
2050 Com	-2.00 to +5.29	-1.37 to +2.06
2050 ResCom	-3.83 to +5.48	-1.41 to +5.61
2050 Ind	-7.10 to +3.58	-1.10 to +12.40
2050 Tra	-2.61 to +1.69	-1.85 to +3.98
2050 Tra Smart	-2.55 to +1.53	-4.17 to +3.61
2050 ResComTra	-3.78 to +4.76	-3.82 to +1.79

Table 20: Summary of peak impacts on 8-hour max ozone and 24-hour $PM_{2.5}$ for winter 2050 Cases

Winter Case	**8-hour Ozone [ppb]**	**24-hour $PM_{2.5}$ [$\mu g/m^3$]**
2050 Res	-10.02 to +3.64	-13.33 to +0.25
2050 Com	-1.60 to +7.27	-4.43 to +0.79
2050 ResCom	-13.45 to +7.46	-20.62 to +1.77
2050 Ind	-13.61 to +5.55	-3.22 to +12.28
2050 Tra	-30.28 to +12.86	-5.89 to +16.32
2050 Tra Smart	-1.15 to +2.26	-3.16 to +1.13
2050 ResComTra	-14.13 to +31.69	-22.34 to +0.20

CHAPTER 5: Conclusions

- Electrification of residential and commercial sectors results in significantly larger load in winter due to high space heating demand, while industrial and transportation electrification scenarios have negligible seasonal variations.
- Residential, commercial and industrial electrification scenarios have the maximum renewable power curtailment caused by nearly flat electrification demand that intensifies the existing grid dynamics, while transportation electrification with smart charging has the lowest curtailment since all of the excess renewable power is used for smart charging of electric vehicles according the renewable power dynamics.
- Transportation electrification with smart charging requires higher generation of power plants around noon as EV smart charging is maximized due to the lower price of electricity during off-peak periods, while still balancing the load without requiring any import from out-of-state resources owing to the assumed high flexibility and availability of the smart EV charging strategy employed.
- The majority of power imports occur during the evening peak, when in-state power generation resources are not sufficient for balancing the grid. In addition, the maximum dynamic emissions occur during this evening peak period, when peaking generators start up and load-following power plants ramp up to generate sufficient power required for balancing the grid.
- The electrification of currently combustion-based end-use technologies in various sectors results in reduced direct criteria pollutant emissions. These reductions in emissions associated with electrification are counter-balanced by increased emissions from power generators supporting new electric loads from increased consumption and the increased emissions due to dynamic ramping of power plants to match the intermittency of uncontrollable renewable power dynamics. As a result, most scenarios show slight air quality dis-benefits associated with electrification and high renewable power use.
- The total annual GHG emissions of end-use sectors (residential, commercial, industrial, transportation) for all of the electrification scenarios investigated are reduced by at least 1 % $MMTCO_2e$ in comparison to the base case, while power sector exhibits GHG emission increases by as much as 47% $MMTCO_2e$ due to dispatch of fossil fuel power plants to meet the additional demand of electrification.
- Overall total GHG emissions are reduced for all of the electrification scenarios in every year considered (2020, 2030, and 2050), while the all sectors electrification scenarios showed the greatest impact on net GHG reductions, up to 25, 91, 111 $MMTCO_2e$ (6.6%, 11.5%, 27.4%) for 2020, 2030, and 2050, respectively.

- The greater GHG emission savings of the Smart Transportation scenario are due to the assumed high flexibility and availability of the EV charging demand and the enhanced load balancing that results from this smart charging strategy. The high energy demand of significant EV charging and the assumed flexibility of smart charging results in zero renewable curtailment, smaller grid dynamics, and consequently lower emissions and air quality improvements.
- Reducing emissions from combustion technologies in various sectors translates to air quality improvements for both ozone and $PM_{2.5}$. Impacts vary markedly by pollutant, sector, horizon year, season, and location. Contrastingly, increased electricity demand from electrification and altered grid dynamics from intermittent renewable penetration can result in localized worsening of air quality at sites of emitting power generators. Increases generally tend to be point sources while decreases occur from both point and area sources. The difference in characteristics between emission source results in differing impacts on the spatial distribution of resulting perturbation to ozone and $PM_{2.5}$. Most of the scenarios exhibited typical increases as point source impacts represented as plumes with higher peak values but over a lesser area. On the other hand most reductions in emissions were from a combination of point sources and area sources.
- It should be considered that not all increases in ground-level ozone concentrations are associated with increased emissions, particularly in urban air sheds with high NOx emissions. It should be considered that these reflect effects relating to the titration reaction and further investigation will be conducted to examine that possibility.
- The deleterious impacts associated with power sector emission increases may be mitigated by advanced complementary strategies such as advanced energy storage, demand response, vehicle-to-grid, and smart charging, and should be considered for co-deployment. Further, such strategies have a range of additional energy and environmental benefits including facilitating much higher levels of renewable power use without significant curtailment.
- Impacts on air quality differ by season as a result of differing generation profiles, demands, and resource availability. Although trends remain similar, different impacts are observed in terms of spatial impacts and to a lesser degree, reduction and increase quantities. For example, an additional area of ozone increase is observed between the Summer Commercial and Winter Commercial Cases. These differences should be considered when considering electrification and renewable resource deployment as strategies to maximize ozone and $PM_{2.5}$ benefits and limit or avoid worsening may not be equivalent from summer to winter. For example, availability of intermittent resources varies from season to season and may be managed differently in terms of temporal integration and balancing strategies at certain times.
- It should be noted that different emission profiles for different sectors arise as a result of various factors and impact the results; for instance, the residential sector demands are

highest in winter due to space heating requirements and thus electrification, emissions, and air quality impacts for those cases are higher in winter than summer.

- For Winter ozone cases, the formation dynamics associated with ozone result in an inverse relationship with NOx emissions; that is to say, increases attributed to sites of decreased emissions and vice versa. However, generally ozone is not a concern during this season due to low solar insolation rates which limit photochemical formation.
- The electrification of the residential and commercial sector demonstrated minor to significant impacts on ozone and $PM_{2.5}$ depending on pollutant, horizon year, and season. Summer impacts are fairly minor as the majority of demand occurs in winter as a result of space heating. In contrast, winter $PM_{2.5}$ impacts demonstrate major improvements throughout the State – particularly in the northern central area of the State. Additionally, commercial sector cases also achieve significant benefits in $PM_{2.5}$ for summer cases. Thus, electrification of the residential and commercial sector should be considered in tandem with high renewable resource deployment, particularly to address $PM_{2.5}$ concerns.
- Electrification of the industrial sector is difficult due to the variation, complexity, and specific nature of industry energy demands, technologies, and processes. Impacts are similarly complex with localized areas of worsening and improvement in both ozone and $PM_{2.5}$. Additionally, in the 2030 and 2050 Cases the demand for electricity from high electrification of industry results in significant deleterious impacts on AQ. It must be considered that electrification in this report pertains to boiler emissions only –industrial process emissions are not reduced. Thus, the results may underestimate the AQ benefits if electrification can be utilized for processes.
- Electrification of the LDV transportation sector at high levels results in moderate improvements in ozone and $PM_{2.5}$ that often occur in important regions including SoCAB and the SF Bay Area. Impacts on air quality are also observable from petroleum fuel infrastructure emission reductions in key regions like Bakersfield and Long Beach. Contrastingly, some worsening occurs from power plant emissions although impacts are generally in regions of the state with less population density. In all horizon years studied the transportation sector cases achieved benefits relative to other cases and the electrification of LDVs could represent an important strategy to improve AQ in tandem with renewable resource deployment.
- The deployment of smart charging achieves a significant AQ benefit relative to immediate charging. It perhaps most notable that despite an increase in required electricity for vehicles the Smart Charging Case does not experience higher areas of worsening from power plants. This is due to the charging strategy which avoids charging during peak times and subsequent emissions. Further, reductions in emissions from generators occur due to the avoidance of ramping during peak periods. The reductions in emissions translate to enhanced reductions in ozone and $PM_{2.5}$ in 2030 of about 1 ppb and 1 $\mu g/m^3$ and in 2050 of -1 ppb and 5.13 $\mu g/m^3$ relative to the immediate

vehicle charging case. Thus, smart charging vehicles can allow for greater vehicle penetrations in tandem with reduced worsening from power plants. Electrification of the LDV sector should consider smart or controlled strategies in seeking AQ benefits.

- Combinations of cases generally result in impacts that are additive. Generally, combination cases enhance benefits to ozone and $PM_{2.5}$, although cases including the industrial sector can still encompass deleterious impacts (for instance, Summer ResComTraInd 2030). The results highlight the challenges associated with industrial sector electrification and further demonstrate the worsening that can occur from increased generator emissions.

GLOSSARY

Term	Definition
AFLOU	Agriculture, Forestry and Other Land Use
ArcGIS	Aeronautical Reconnaissance Coverage Geographic Information System
BAU	Business as Usual
BEV	Battery Electric Vehical
CAISO	California Independent System Operator
CHP	Combined Heat and Power
DR	Demand Response
eGRID	Emissions & Generation Resource Integrated Database
EIA	Energy Information Administration
GHG	Greenhouse Gas Emission
GIS	Geographic Information System
HiGRID	Holistic Grid Resource Integration and Deployment
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
LPG	Liquefied Petroleum Gas
MARKAL	Market Allocation
PHEV	Plug-In Hybrid Electric Vehicle
PV	Photovoltaics
RPS	Renewable Portfolio Standard
SMOKE	Sparse Matrix Operator Kernel Emissions
SoCAB	South Coast Air Basin
WECC	Western Electricity Coordinating Council
ZEV	Zero Emission Vehicle

REFERENCES

Ahearne, J. F., 2011. Prospects for nuclear energy. *Energy Economics,* pp. 572-580.

Air Quality Planning and Science Division, ARB, 2013. *THE CALIFORNIA ALMANAC OF EMISSIONS AND AIR QUALITY,* Sacramento: California Air Resources Board.

Air Resources Board, 2008. *Overview of the harmful health effects of ground level ozone,* Sacramento, CA: California Environmental Protection Agency.

Air Resources Board, 2009. *California Ambient Air Quality Standards,* Sacramento, CA: California Environmental Protection Agency.

Akimoto, H., 2003. Global Air Quality and Pollution. *Science,* pp. 1716-1719.

American Council for an Energy-Efficient Economy, 2012. *ACEEE Space Heating.* [Online] Available at: http://www.aceee.org/consumer/heating

American Council for an Energy-Efficient Economy, 2012. *ACEEE Water Heating.* [Online] Available at: http://www.aceee.org/consumer/water-heating

Appel, K. W., Roselle, S. J., Gilliam, R. C. & Pleim, J. E., 2010. Sensitivity of the Community Multiscale Air Quality (CMAQ) model v4.7 results for the eastern United States to MM5 and WRF meteorological drivers. *Geoscientific Model Development,* 3(1), p. 169–188.

Appel, W. K. et al., 2008. Evaluation of the community multiscale air quality (CMAQ) model version 4.5: Sensitivities impacting model performance; Part II - particulate matter. *Atmospheric Environment,,* 42(24), p. 6057–6066.

Arizona Department of Environemtnal Quality, n.d. *Particulate Matter Health Information Fact Sheet,* Phoenix, AZ: AZDEQ.

Bauen, A., 2006. Future energy sources and systems—Acting on climate. *Journal of Power Sources,* pp. 893-901.

Bielecki, J., 2002. Energy security: is the wolf at the door?. *The Quarterly Review of Economics and Finance,* pp. 235-250.

Brunekreef, B. & Holgate, S. T., 2002. Air pollution and health. *THE LANCET,* pp. 1233-1242.

Bureau of Economic Analysis, 2014. *U.S. Department of Commerce.* [Online] Available at: http://www.bea.gov/iTable/index_nipa.cfm
[Accessed 4 March 2015].

Byun, D. & Ching, J., 1999. *Science algorithms of the EPA Models-3 community multiscale air quality (CMAQ) modeling system*, s.l.: US EPA.

California Air Resources Board, 2014. *California Greenhouse Gas Emission Inventory: 2000-2012,* Sacramento: California Environmental Protection Agency, ARB.

California Energy Commission, 2010. *Energy Consumption by Standard Industrial Classification,* Sacramento CA: CEC.

California Energy Commission, 2013. *California Energy ALMANAC.* [Online] Available at: http://energyalmanac.ca.gov/electricity/total_system_power.html [Accessed December 2014].

California Independent System Operator, 2010. *Integration of Renewable Resources: Operational Requirments and Generation Fleet Capability*, s.l.: CAISO.

CARB, 2009. *CEPAM: 2009 Almanac - Standard Emissions Tool.* [Online] Available at: http://www.arb.ca.gov/app/emsinv/fcemssumcat2009.php [Accessed December 2013].

CARB, 2013. *CEPAM: 2013 Almanac - Standard Emissions Tool.* [Online] Available at: http://www.arb.ca.gov/app/emsinv/fcemssumcat2013.php [Accessed December 2014].

CARB, 2014. *California Greenhouse Gas Emission Inventory.* [Online] Available at: http://www.arb.ca.gov/cc/inventory/inventory_current.htm [Accessed 12 2014].

CEC Demand Analysis Office, 2012. *Residential Natural Gas Consumption By End Use.* [Online] Available at: http://energyalmanac.ca.gov/naturalgas/residential_use.html [Accessed May 2015].

CEC Energy Assessments Division, 2014. *California Energy Consumption by End Use.* [Online] Available at: http://energyalmanac.ca.gov/electricity/electricity_stats/index.html [Accessed April 2015].

Chen, B. & Kan, H., 2008. Air pollution and population health: a global challenge. *Environmental Health and Preventive Medicine,* pp. 94-101.

Chu, S. & Majumda, A., 2012. Opportunities and challenges for a sustainable energy future. *NATURE,* pp. 294-303.

DOUGLAS, P., STOLTZFUS, E., GILLETTE, A. & MARKS, J., 2009. *33% RPS Implementation Analysis Preliminary Results,* s.l.: California Public Utilities Commission.

Drayton, G., 2014. *PLEXOS 6.301..* s.l.:Energy Exemplar.

Eichman, J. et al., 2012. Exploration of the integration of renewable resources into California's electric system using the Holistic Grid Resource Integration and Deployment (HiGRID) tool. *Energy.*

Environmental Protection Agency, 2012. *Emissions & Generation Resource Integrated Database (eGRID).* s.l.:Environmental Protection Agency.

Epstein, P. R., 2000. Is Global Warming Harmful to Human Health?. *Scientific American,* pp. 50-57.

Fenger, J., 2008. Air pollution in the last 50 years – From local to global. *Atmospheric Environment,* pp. 13-22.

Fishbone, L. G. & Abilock, H., 1981. MARKAL: A linear programming model for energy-systems analysis: technical description of the BNL version. *International Journal of Energy Research ,* 5(4), pp. 353-375.

Foley, K. M. et al., 2010. Incremental testing of the Community Multiscale Air Quality (CMAQ). *Geoscientific Model Development,* 3(1), pp. 205–226,.

Friedmann, R., Coito, F., Worrell, E. & Rufo, M., 2005. *California Industrial Energy Efficiency Potential,* s.l.: American Council for an Energy-Efficient Economy (ACEEE).

Greenblatt, J., Wei, M. & McMahon, J., November 2012. *California's Energy Future: Building and Industrial Efficiency,* s.l.: Lawrence Berkeley National Laboratory.

Greening, L., Boyd, G. & Roop, J., 2007. Modeling of Industrial Energy Consumption: An introduction and context. *Energy Economics,* 29(4), pp. 599-608.

Heling, M. G., Saphores, J.-D. & Samuelson, G. S., 2008. *User Characteristics and Reponses to a Shared-Use Station Car Program: An Analysis of ZEV•NET in Orange County, CA,* s.l.: UCI Institute of Transportation Studies.

Hirsch, J. J., 1998-2014. *eQuest Quick Energy Simulation Tool.* s.l.:DOE2.

Hughes, L., 2009. The four 'R's of energy security. *Energy Policy,* p. 2459–2461.

Intergovernmental Panel on Climate Change, 2014. *Climate Change 2014: Impacts, Adaptation, and Vulnerability,* Cambridge, United Kingdom and NewYork, NY, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change, 2014. *Climate Change 2014: Mitigation of Climate Change,* Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Intergovernmental Panel on Climate Change, 2014. *Climate Change 2014: Synthetic Report,* s.l.: s.n.

Itron Inc., 2006. *California Commercial End-use Survey,* Sacramento, CA: California Energy Comission.

KEMA Inc., 2010. *2009 CALIFORNIA RESIDENTIAL APPLIANCES SATURATION STUDY,* s.l.: California Energy Commission.

Lave, L. B., 2009. *The Potential of Energy Efficiency: An Overview,* Washington, DC: National Academy of Engineering.

Lawrence Berkeley National Laboratory, 2007. *Improving Process Heating System Performance,* s.l.: U.S. Department of Energy.

Loughlin, D. H., Benjey, W. G. & Nolte, C. G., 2011. ESP v1.0: methodology for exploring emission impacts of future scenarios in the United States. *Geoscientific Model Development,* Volume 4, pp. 287-297.

Loulou, R., Goldstein, G. & Noble, K., 2004. *Documentation for the MARKAL Family of Models,* s.l.: Energy Technology Systems Analysis Programme.

Luecken, D., Phillips, S., Sarwar, G. & Jang, C., 2008. Effects of using the CB05 vs. SAPRC99 vs. CB4 chemical mechanism on model predictions: Ozone and gas-phase photochemical precursor concentrations. *Atmospheric Environment,* Volume 42, p. 5805–5820.

Mai, T., Mulcahy, D., Hand, M. M. & Baldwin, S. F., 2014. Envisioning a renewable electricity future for the United States. *Energy,* pp. 374-386.

McCarthy, R., Yang, C. & Ogden, J., n.d. *California Baseline Energy Demands to 2050 for Advanced Energy Pathways,* s.l.: UC Davis Institute of Transportation Studies.

McCollum, D. et al., 2014. Fossil resource and energy security dynamics in conventional and carbon-constrained worlds. *Climatic Change,* p. 413–426.

McDonald, B. C., Dallmann, T. R., Martin, E. W. & Harley, R. A., 2012. Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales. *JOURNAL OF GEOPHYSICAL RESEARCH,* pp. 1-11.

Medrano, M. & Brouwer, J., 2008. A methodology for developing Distributed Generation scenarios in urban areas using geographical information systems. *International Journal of Energy Technology and Policy,* 6(4), pp. 413-434.

Meehl, G. A. et al., 2005. How Much More Global Warming and Sea Level Rise?. *Science,* Volume 307, pp. 1769-1772.

Mez, L., 2012. Nuclear energy–Anysolutionforsustainabilityandclimateprotection?. *Energy Policy,* pp. 56-63.

National Academy of Engineering, 2010. *Real Prospects for Energy Efficiency in the United States,* Washington, DC: National Academy of Sciences.

National Renewable Energy Laboratory, 2010. *Western Wind and Solar Integration Study,* s.l.: NREL.

NCEP , 2005. *FNL Operational Model Global Tropospheric Analyses.* [Online]
Available at: http://rda.ucar.edu/datasets/ds083.2.
[Accessed January 2012].

Peters, G. P. et al., 2013. The challenge to keep global warming below 2 °C. *NATURE CLIMATE CHANGE,* pp. 4-6.

Rafaj, P., Kypreos, S. & Barreto, L., 2005. Flexible Carbon Mitigation Policies: Analysis with a Global Multi-Regional MARKAL Model. In: A. Haurie & L. Viguier, eds. *THE COUPLING OF CLIMATE AND ECONOMIC DYNAMICS.* s.l.:Springer, pp. 237-266.

Renssen, S. V., 2012. An energy revolution. *NATURE CLIMATE CHANGE,* pp. 19-20.

SCHMIDT, P. S., 1987. ELECTRICITY AND INDUSTRIAL PRODUCTIVITY: A TECHNICAL AND ECONOMIC PERSPECTIVE. *ENERGY,* 12(10-11), pp. 1111-1120.

Seaton, A., MacNee, W., Donaldson, K. & Godden, D., 1995. Particulate air pollution and acute health effects. *THE LANCENT,* pp. 176-178.

Skamarock, W. C. et al., 2005. *A description of the Advanced Research WRF Version 2,* s.l.: NCAR Tech Notes -468+STR.

Sovacool, B. K. & Brown, M. A., 2010. Competing Dimensions of Energy Security: An International Perspective. *The Annual Review of Environment and Resources,* pp. 77-104.

Tan, A. & Brouwer, J., 2013. *Spatially and Temporally Resolved Emissions Impacts of Renewable Energy Integration into the Electric Grid,* s.l.: s.n.

U.S. Department of Energy, E. I. A., 2009. *Household Energy Use in California,* s.l.: DOE/EIA.

U.S. Department of State, 2010. *U.S. Climate Action Report 2010,* s.l.: Washington: Global Publishing Services.

U.S. EIA, 2014. *Annual Energy Outlook 2014: with projections to 2040,* s.l.: Energy Information Administration, U.S. Department of Energy.

U.S. Energy Information Administration, 2012. *State Energy Consumption Estimates,* Washington, DC: U.S. EIA.

U.S. Energy Information Administration, 2012. *State Profile and Energy Estimates of California,* s.l.: U.S. EIA.

U.S. Energy Information Administration, 2014. *Annual Energy Outlook,* s.l.: U.S. Department of Energy.

U.S. EPA, 2011. *Emissions Modeling Clearinghouse.* [Online]
Available at: http://www.epa.gov/ttn/chief/emch/index.html
[Accessed December 2014].

U.S. EPA, 2014. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012,* s.l.: U.S. Environmental Protection Agency.

Umbach, F., 2010. Global energy security and the implications for the EU. *Energy Policy,* pp. 1229-1240.

US Census Bureau, 2014. *Population Estimates.* [Online]
Available at: http://www.census.gov/popest/data/historical/index.html
[Accessed 4 March 2015].

US Environmental Protection Agency, 2006. *MARKAL scenario analysis of technology options for the electric sector: The impact on air quality*, Washington, DC: US EPA.

Wei, M. et al., 2013. Deep carbon reductions in California require electrification and integration across economic sectors. *ENVIRONMENTAL RESEARCH LETTERS.*

Wigley, T. M. L., 2005. The Climate Change Commitment. *Science,* Volume 307, pp. 1766-1769.

Williams, J. H. et al., 2012. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *Science Magazine,* pp. 53-58.

Williams, J. H. et al., 2012. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *Science,* pp. 53-59.

Wilson, L., 2013. *Heating Cost Comparison: Oil vs Gas vs Electric Prices.* [Online]
Available at: http://theenergycollective.com/lindsay-wilson/307486/heating-cost-comparison-oil-heat-vs-gas-heat-vs-electric-heat-prices

Yokoyama, T., 2009. Progress & Challenges for Toyota's Fuel Cell Development. s.l., s.n